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Brooks et al.

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(54) **ACTUATION MECHANISMS FOR LOAD MANAGEMENT DEVICES ON AERODYNAMIC BLADES**

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F03D 7/02 (2006.01)
F03D 1/06 (2006.01)

(52) **U.S. Cl.**
CPC ***F03D 7/022*** (2013.01); ***F03D 1/0675*** (2013.01); ***F03D 7/0256*** (2013.01); ***F03D 80/00*** (2016.05);
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(58) **Field of Classification Search**
CPC F03D 1/0675; F03D 7/022; F03D 7/0256; F03D 11/00; F05B 2240/122; F05B 2240/31; F05B 2260/507
USPC 416/23
See application file for complete search history.

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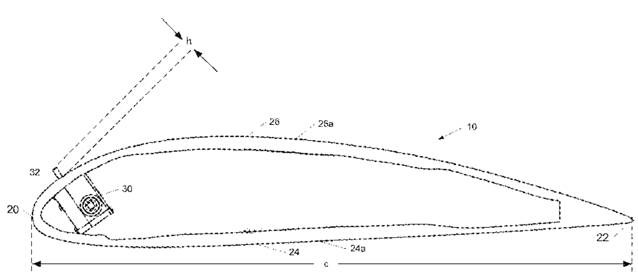
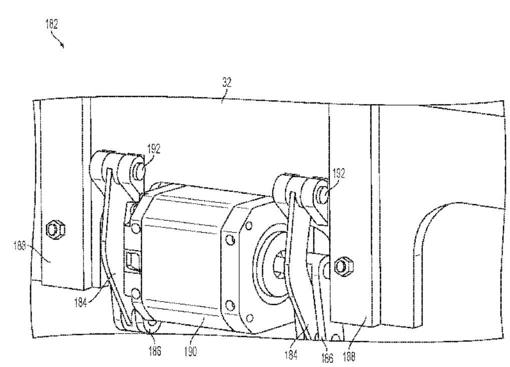
(74) *Attorney, Agent, or Firm* — Banner & Witcoff, Ltd.

(57) **ABSTRACT**

Systems, apparatuses, and methods are provided for actuating one or more load management devices on a wind turbine and/or a wind turbine blade. Each actuator may exhibit one or more beneficial qualities including appropriate actuation speed/force characteristics, size and/or weight characteristics, and/or increased reliability and consistent operation in a variety of operating conditions. According to some aspects, the actuator may be a direct pneumatic actuator, a ramp slide pneumatic actuator, a scissor actuator, a linear induction actuator, a belt actuator, a closed cam follower actuator, a screw drive actuator, a solenoid actuator, a rack and pinion actuator, a cylindrical cam follower actuator, a Y-belt actuator, an offset rotary drive actuator, a tape style actuator, a rigid tape actuator, a deformable membrane actuator, a memory alloy actuator, and/or a crank slide actuator.

20 Claims, 28 Drawing Sheets





(52) **U.S. Cl.**
CPC *F05B 2240/122* (2013.01); *F05B 2240/31* (2013.01); *F05B 2260/507* (2013.01); *Y02E 10/721* (2013.01); *Y02E 10/722* (2013.01); *Y02E 10/723* (2013.01)

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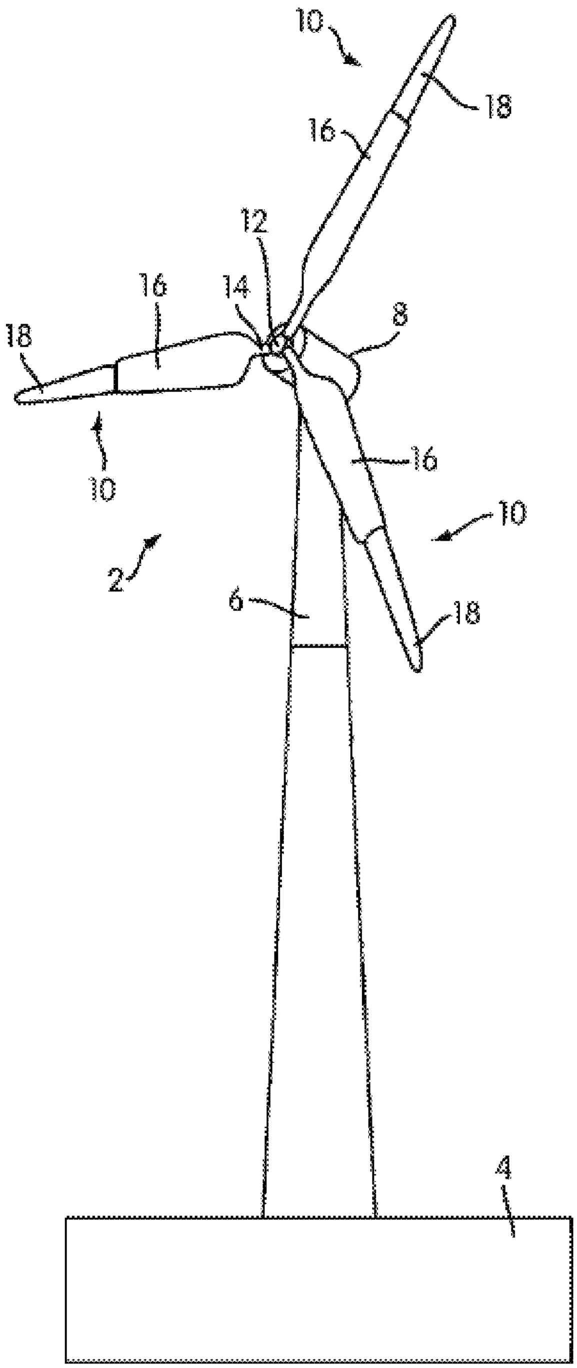


FIG. 1

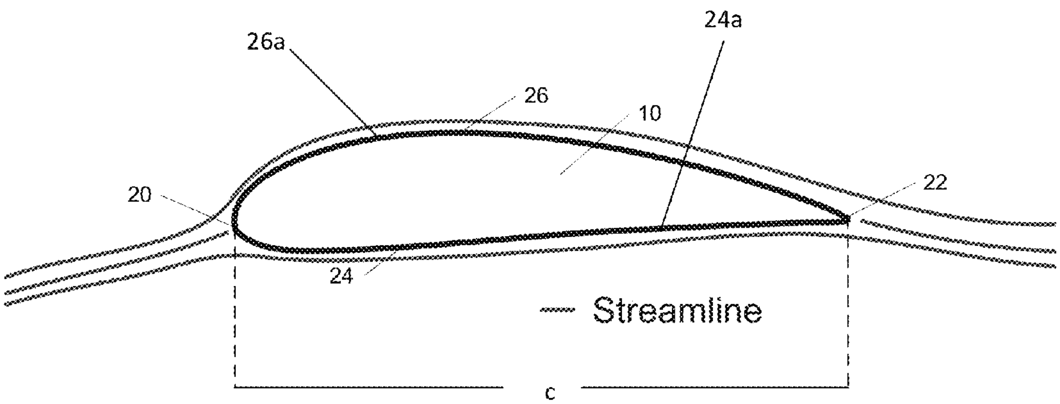

26a
24a
26
10
20
22
24
Streamline
c

FIG. 2

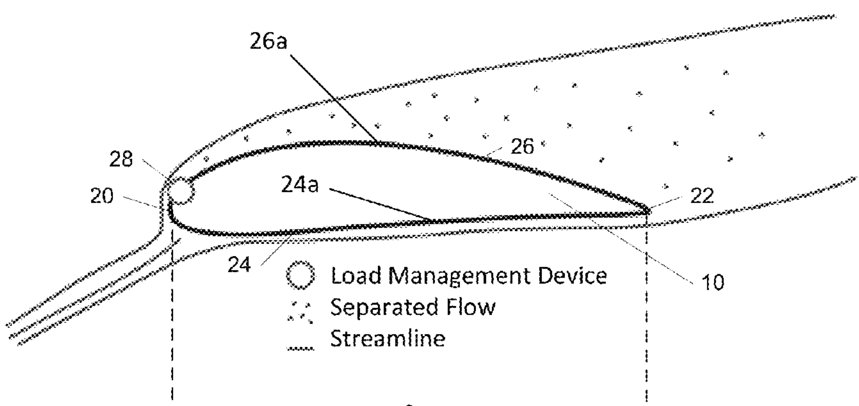

26a
28
26
20
24a
22
24
10
Load Management Device
Separated Flow
Streamline
c

FIG. 3

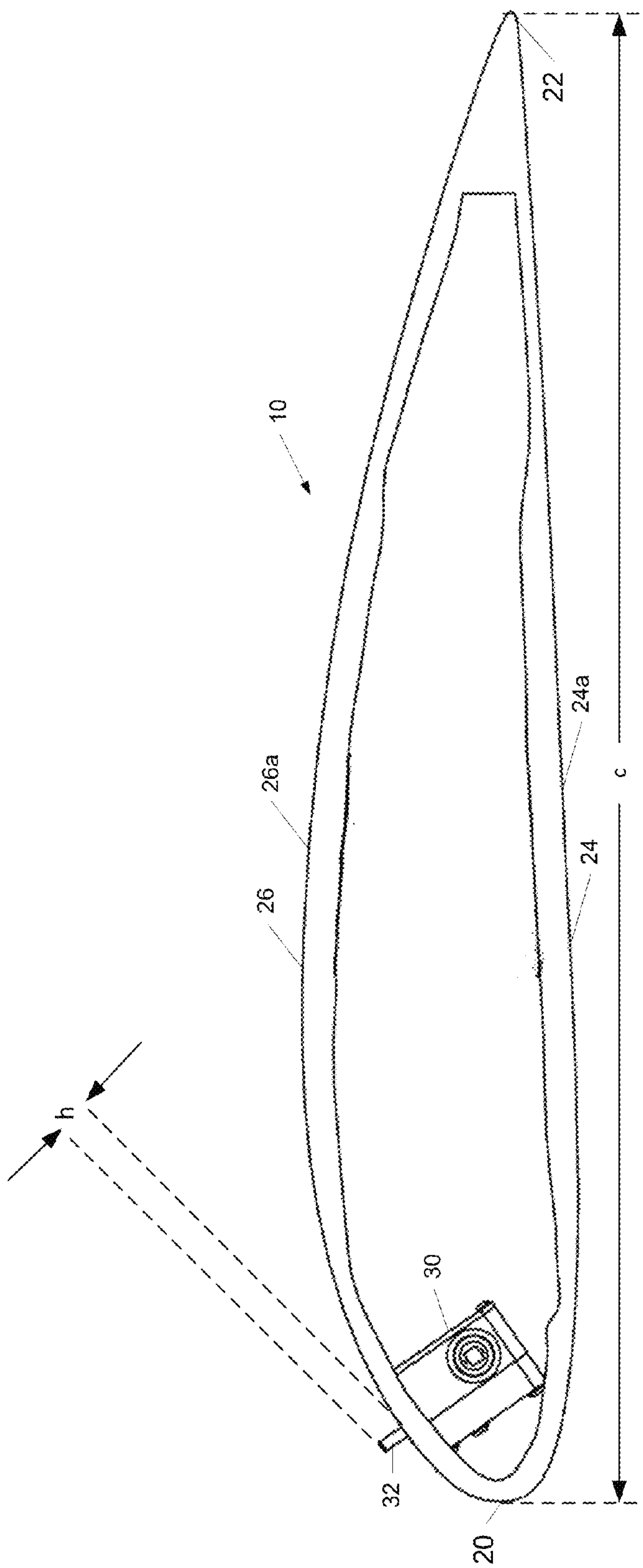


FIG. 4

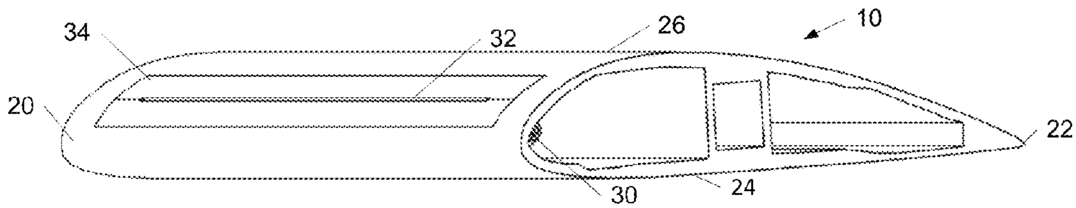


FIG. 5

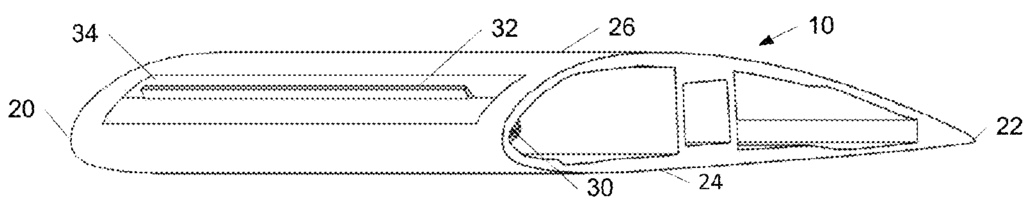


FIG. 6

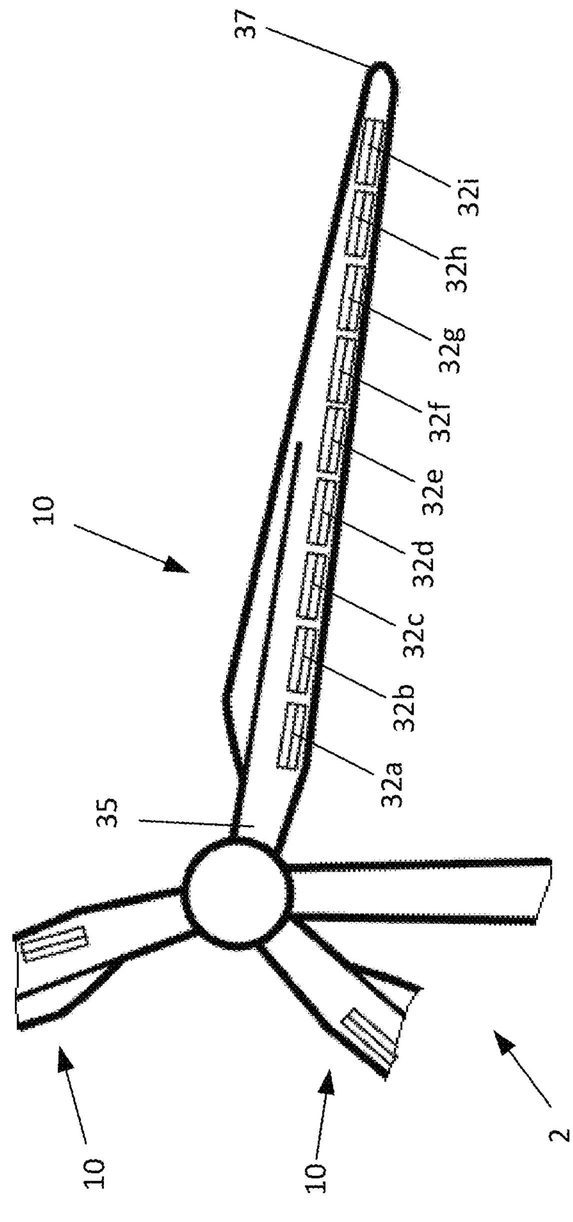


FIG. 7

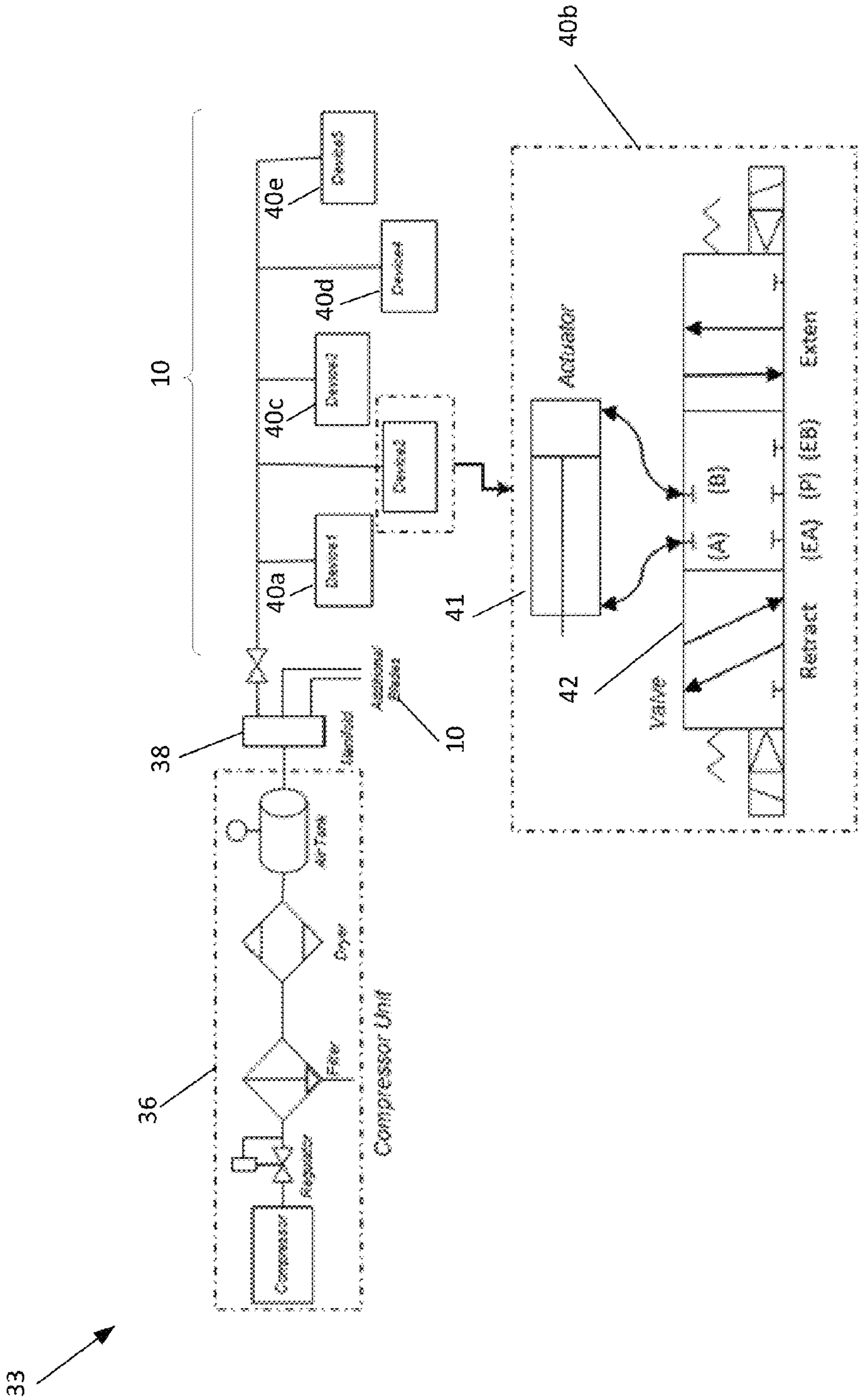

40b
10
40e
40d
40c
40a
Actuator
41
42
(A)
(B)
(EA)
(P)
(EB)
Exten
Retract
Valve
38
10
36
Compressor Unit
33

FIG. 8

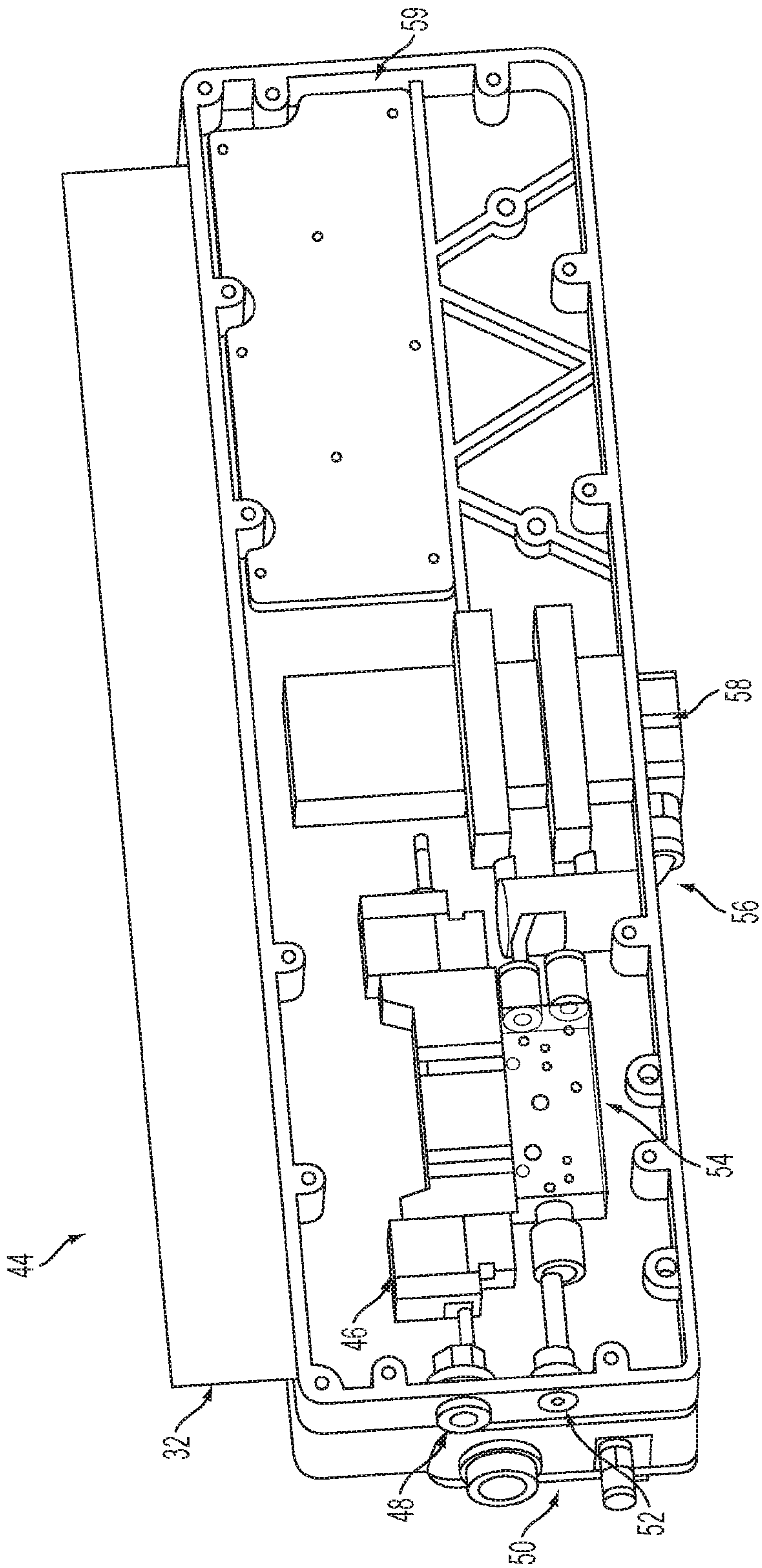


FIG. 9

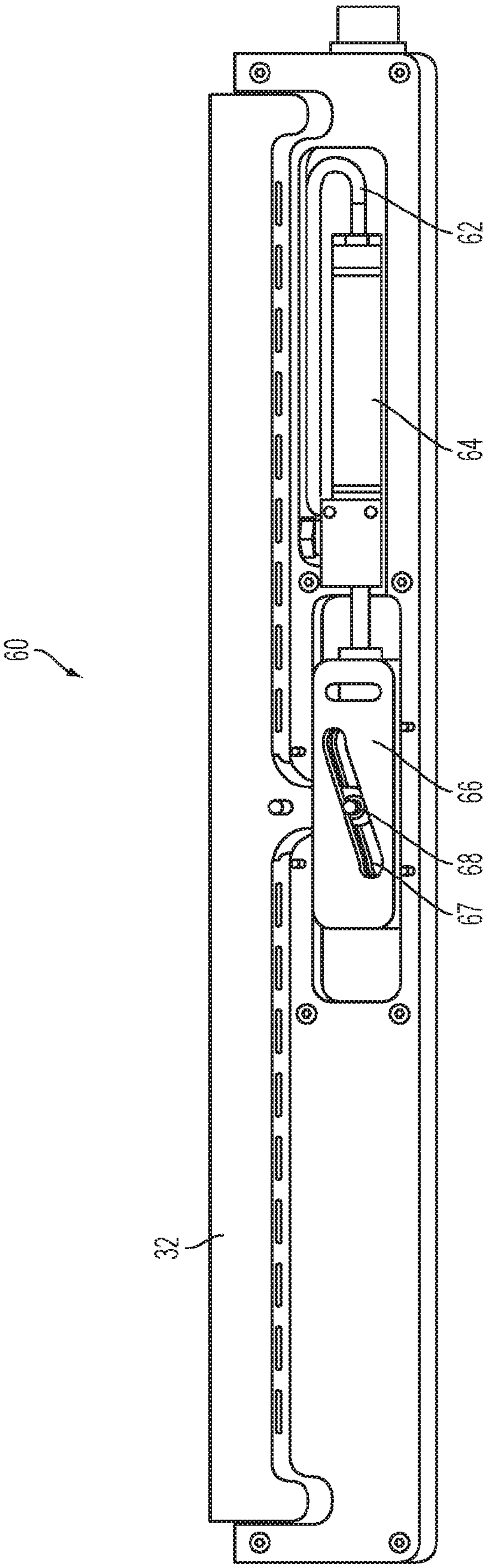


FIG. 10

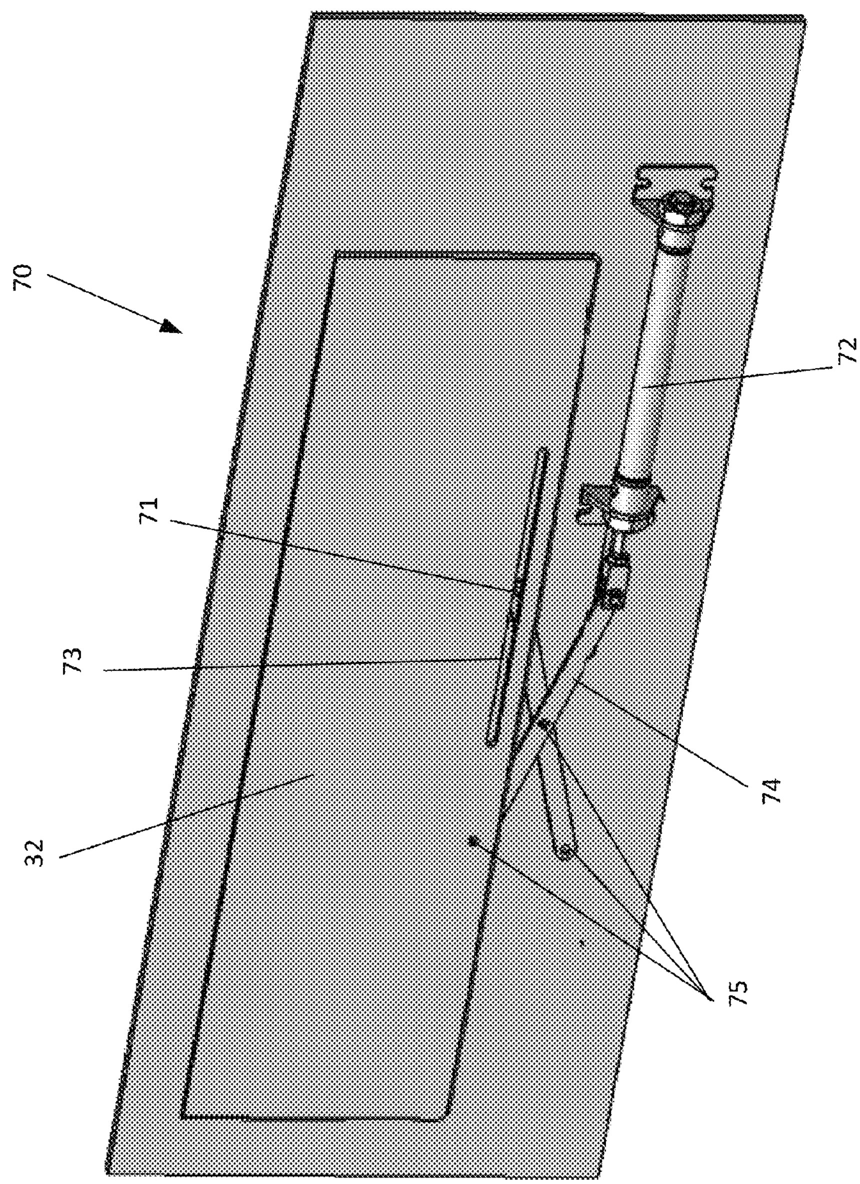


FIG. 11

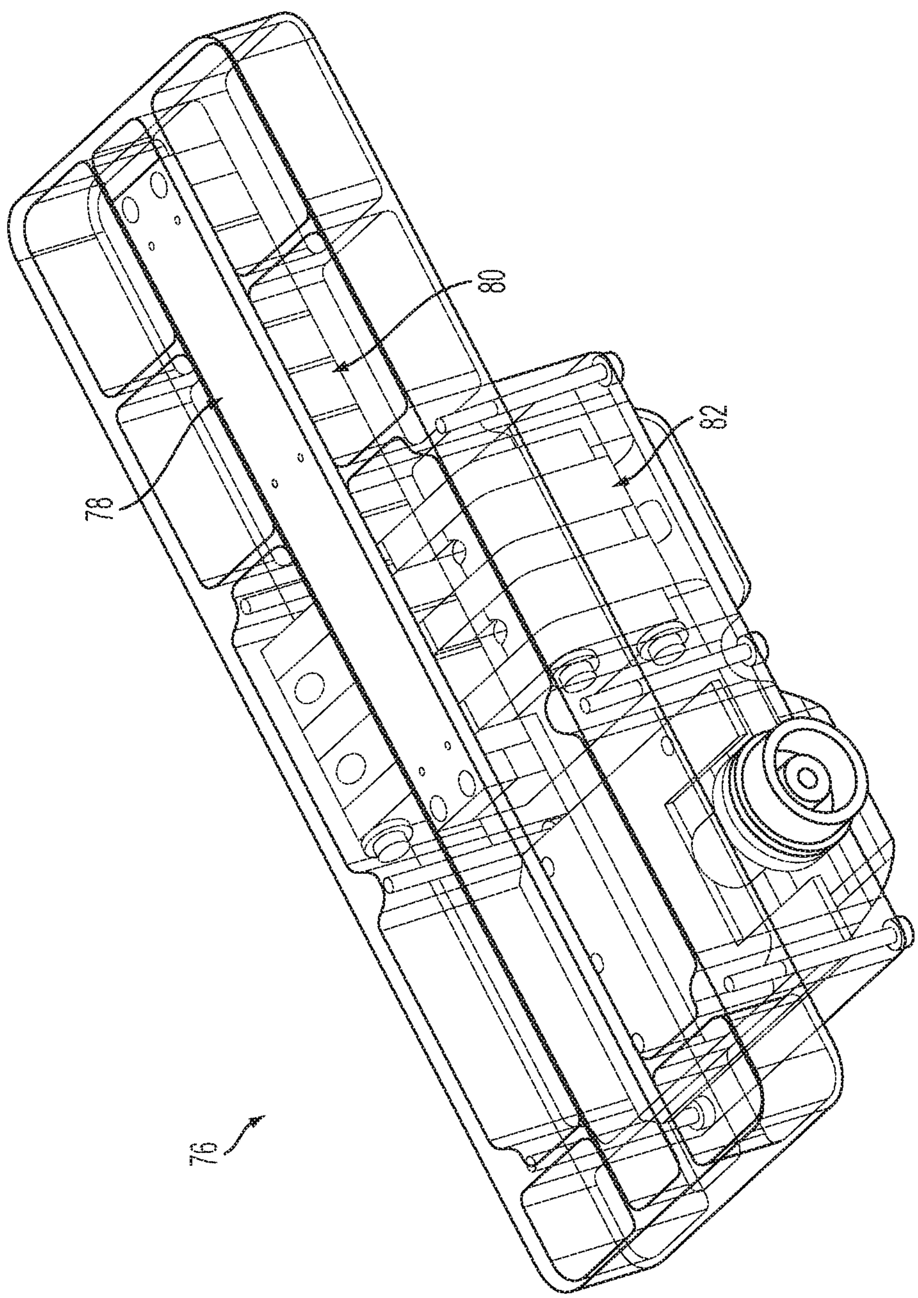


FIG. 12

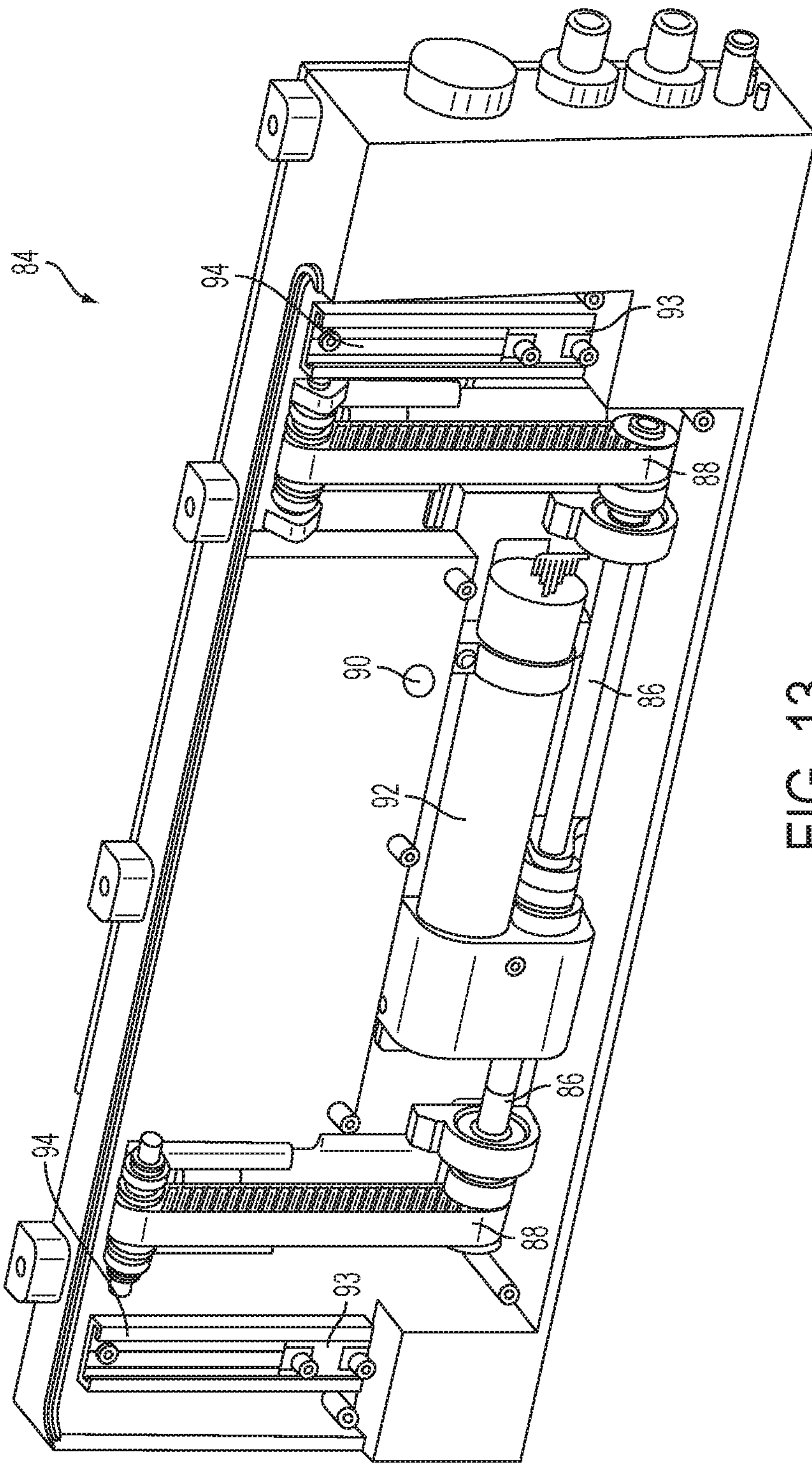


FIG. 13

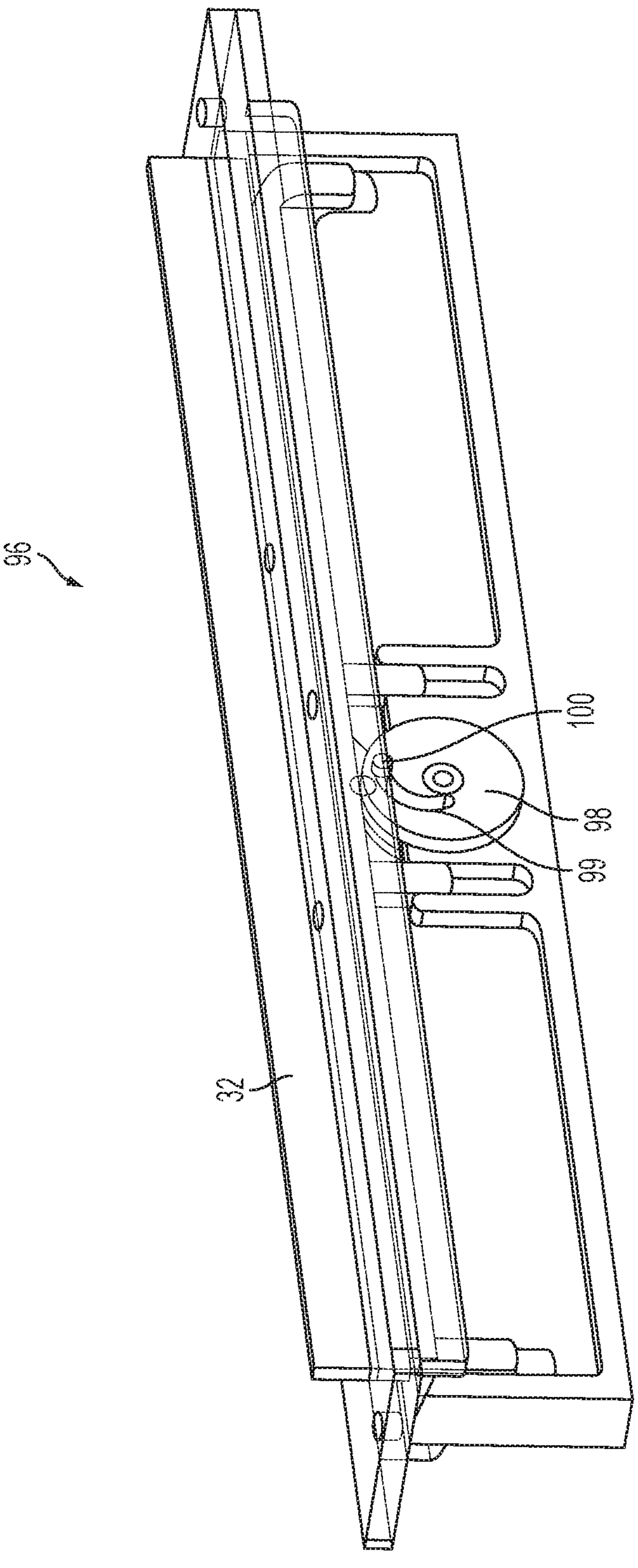


FIG. 14

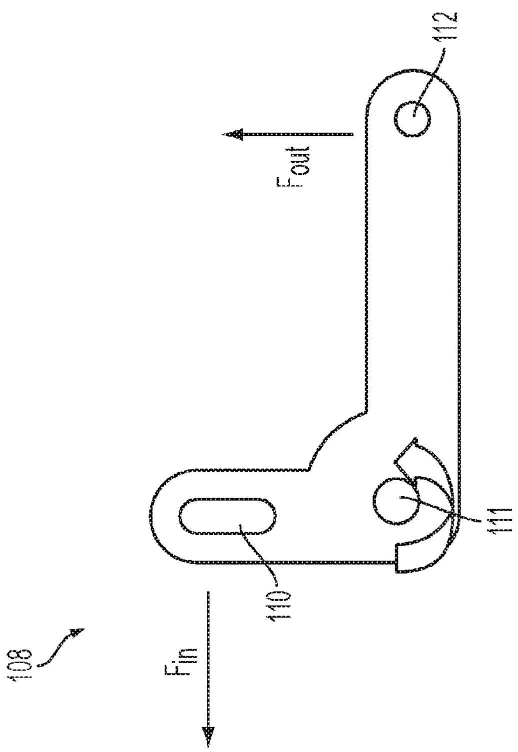


FIG. 16

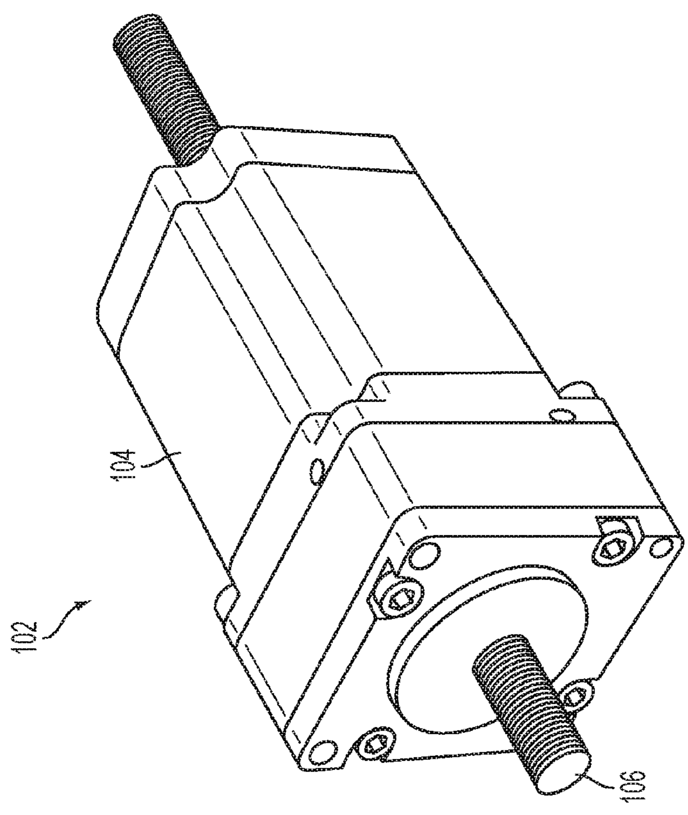


FIG. 15

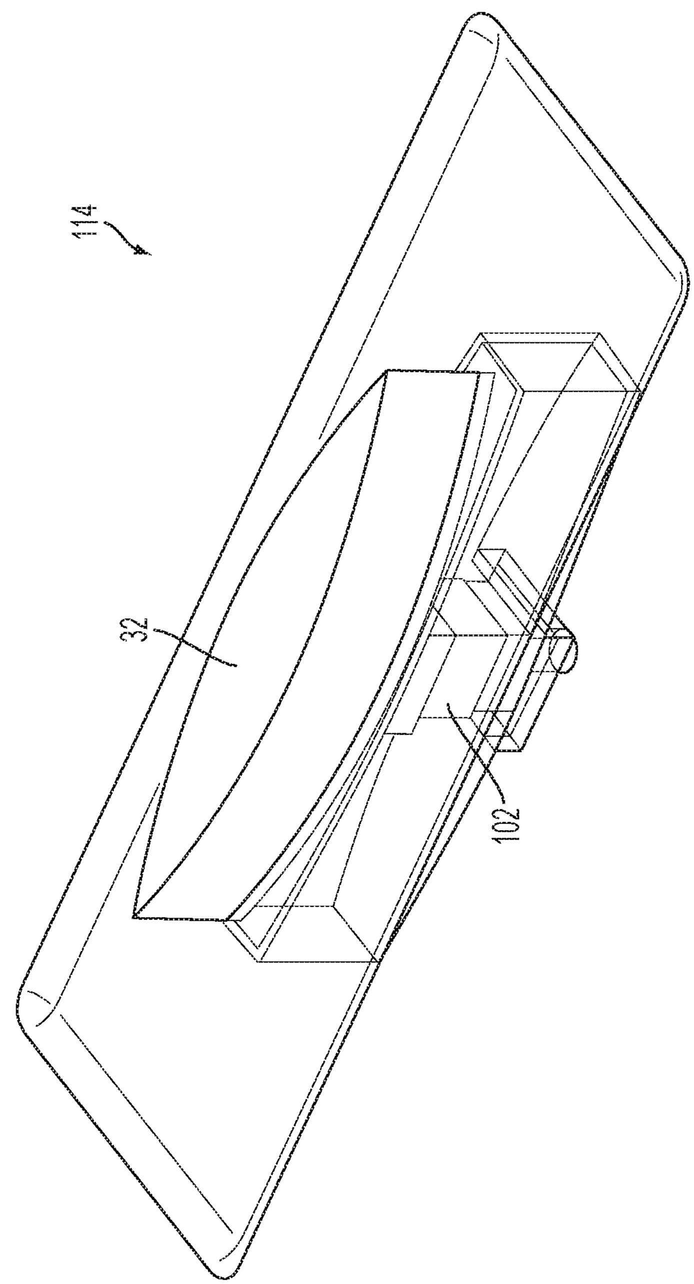


FIG. 17

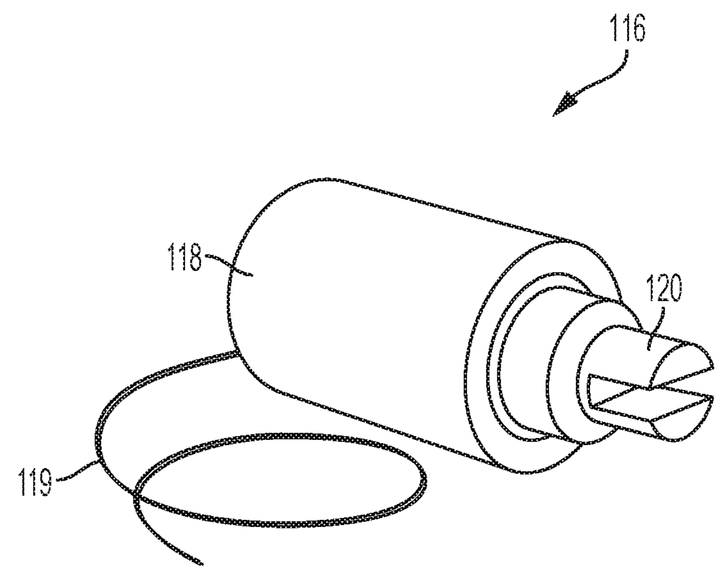


FIG. 18

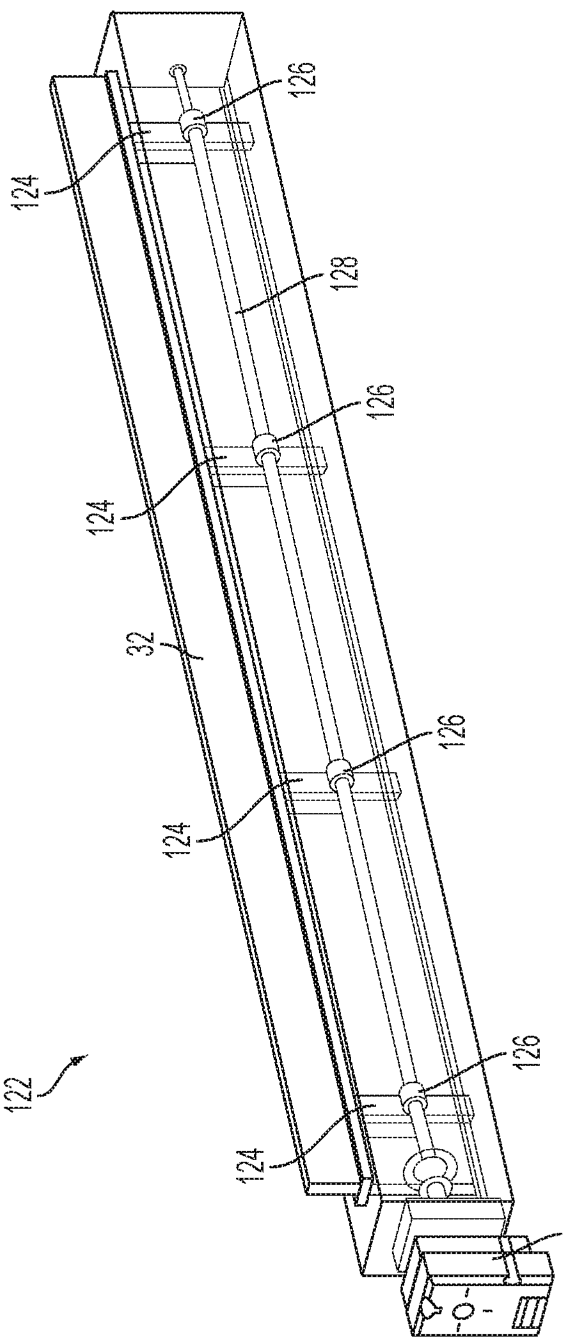
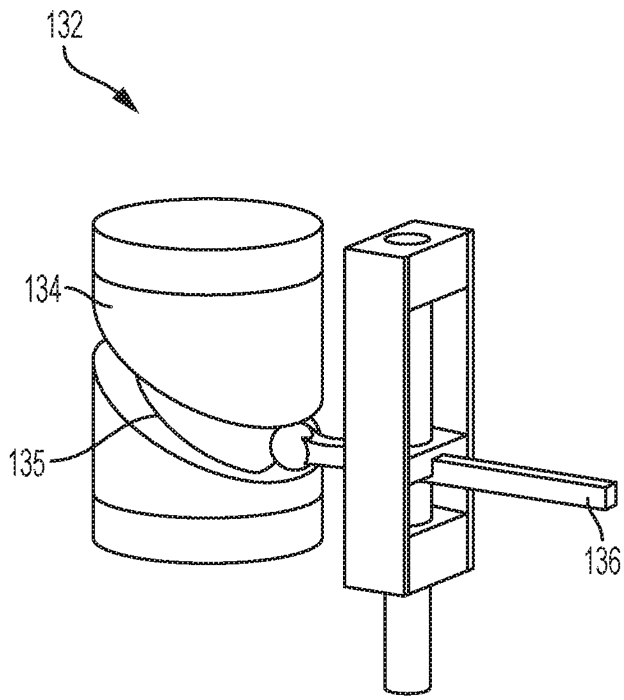


FIG. 19



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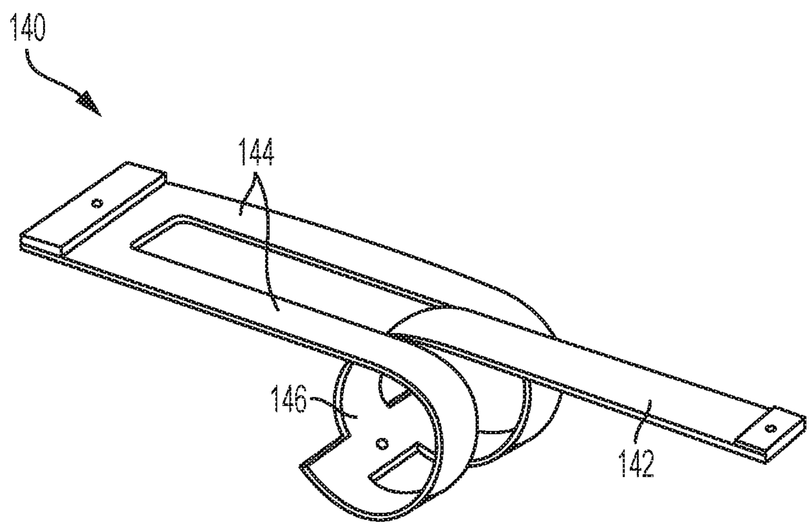

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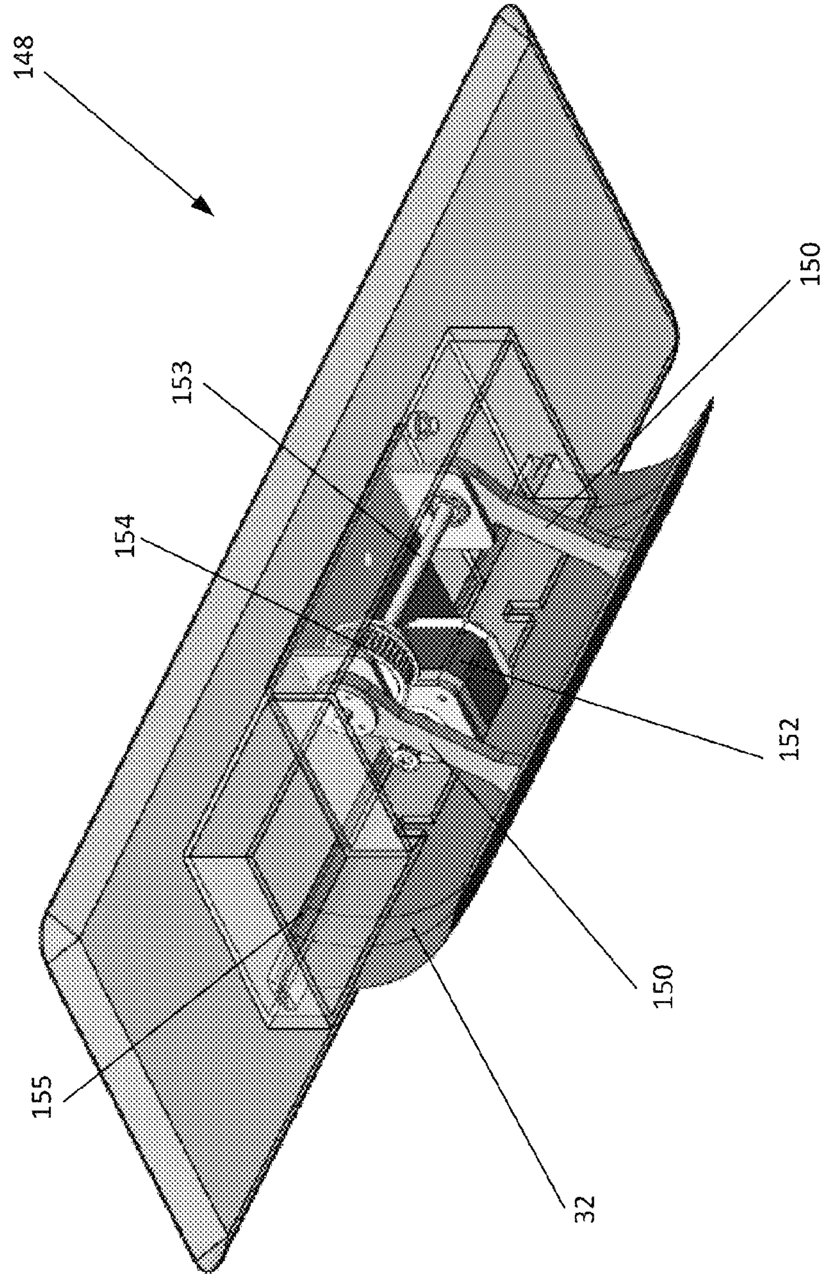

FIG. 22

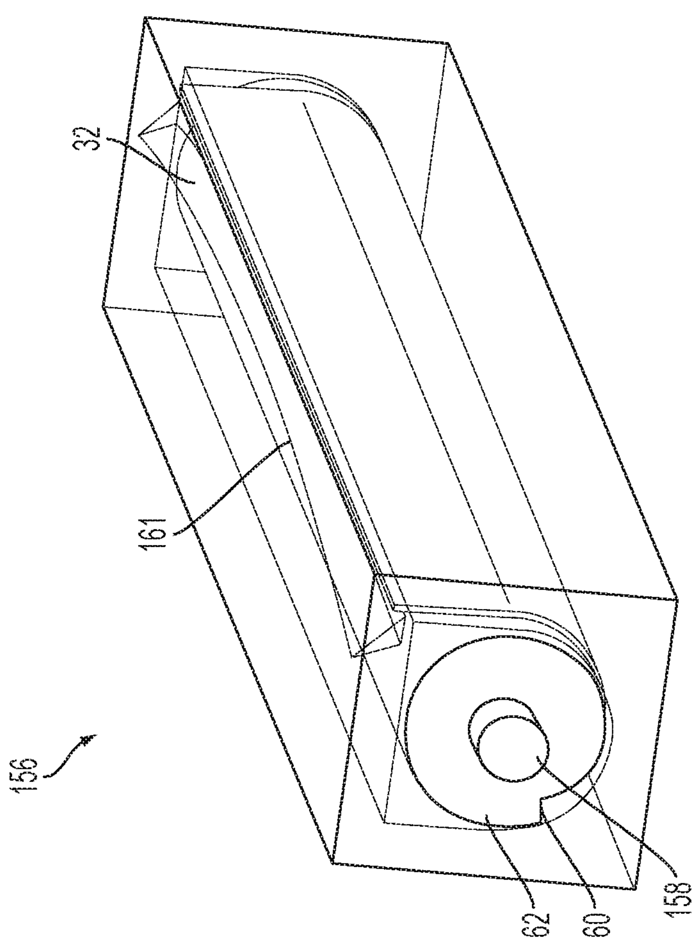

FIG. 23

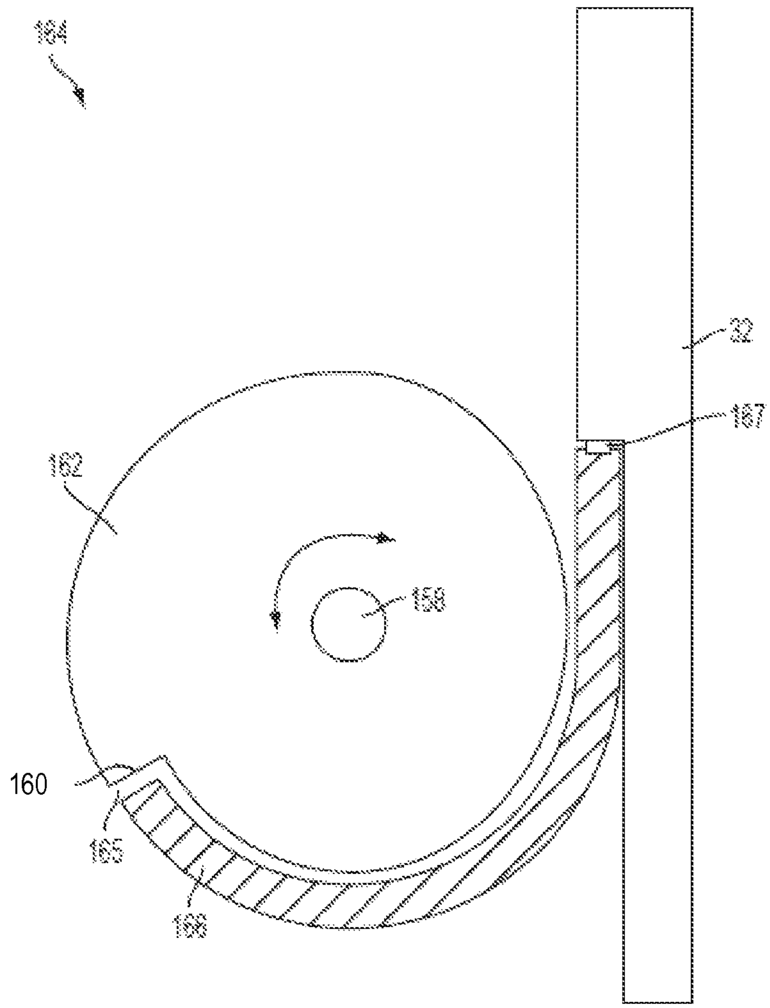

FIG. 24

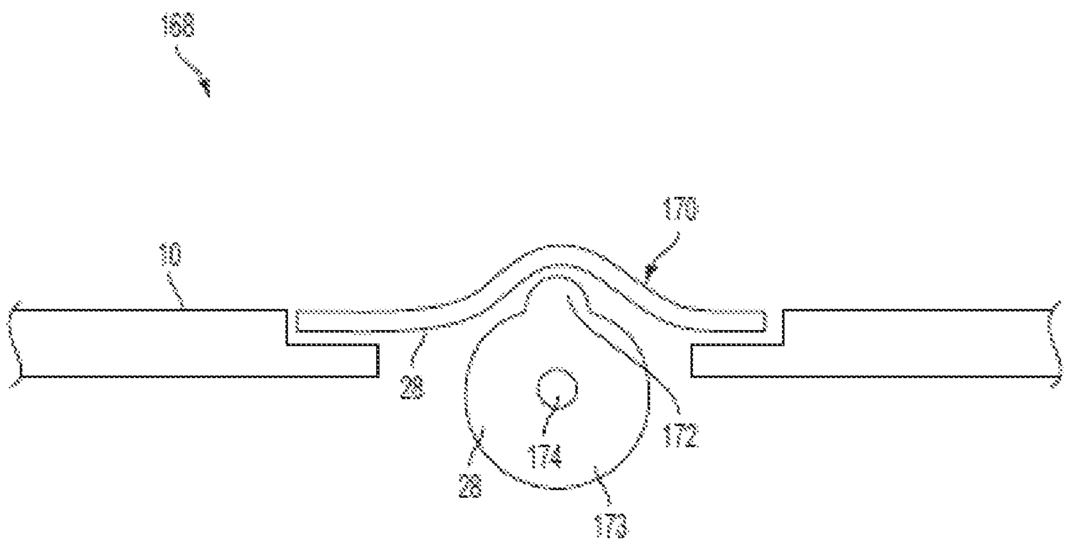

FIG. 25

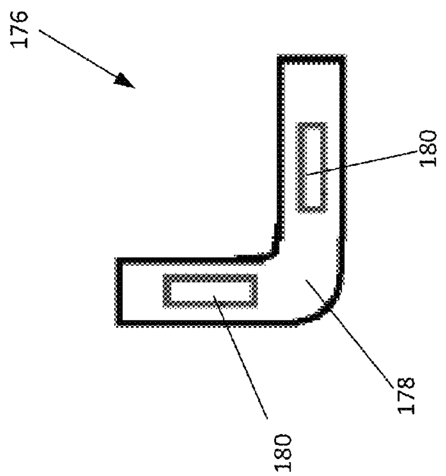

FIG. 26b

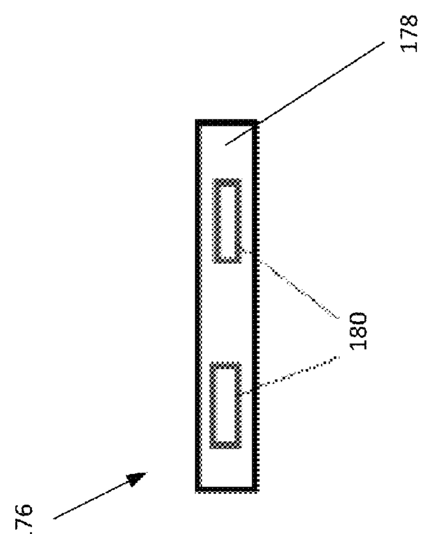

FIG. 26a

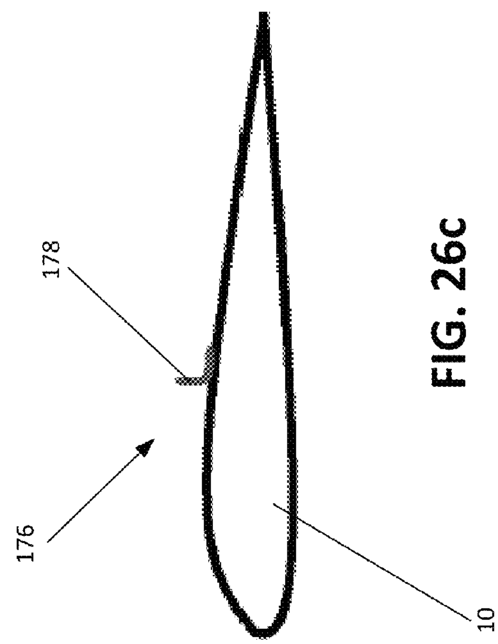

FIG. 26c

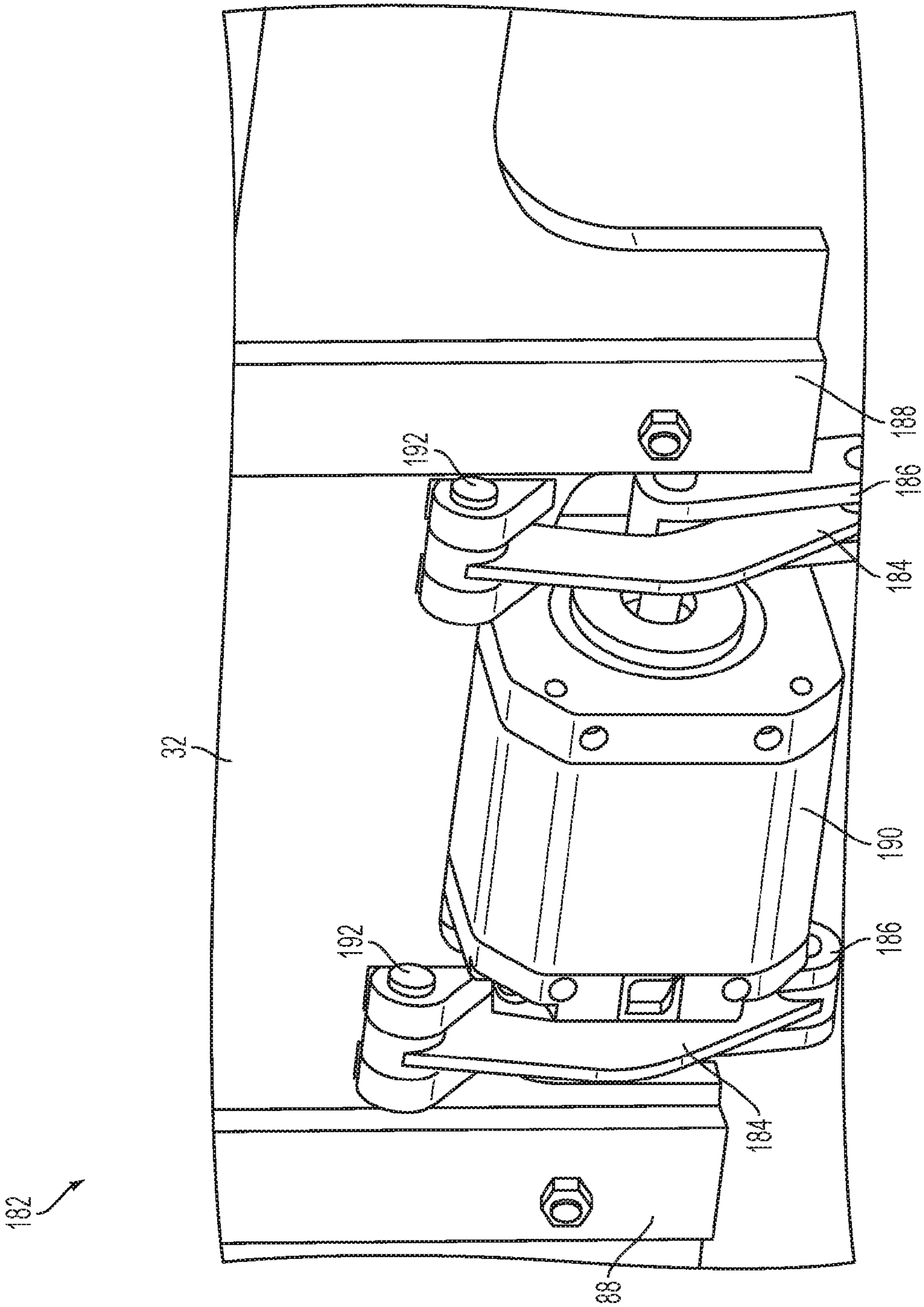

FIG. 27a

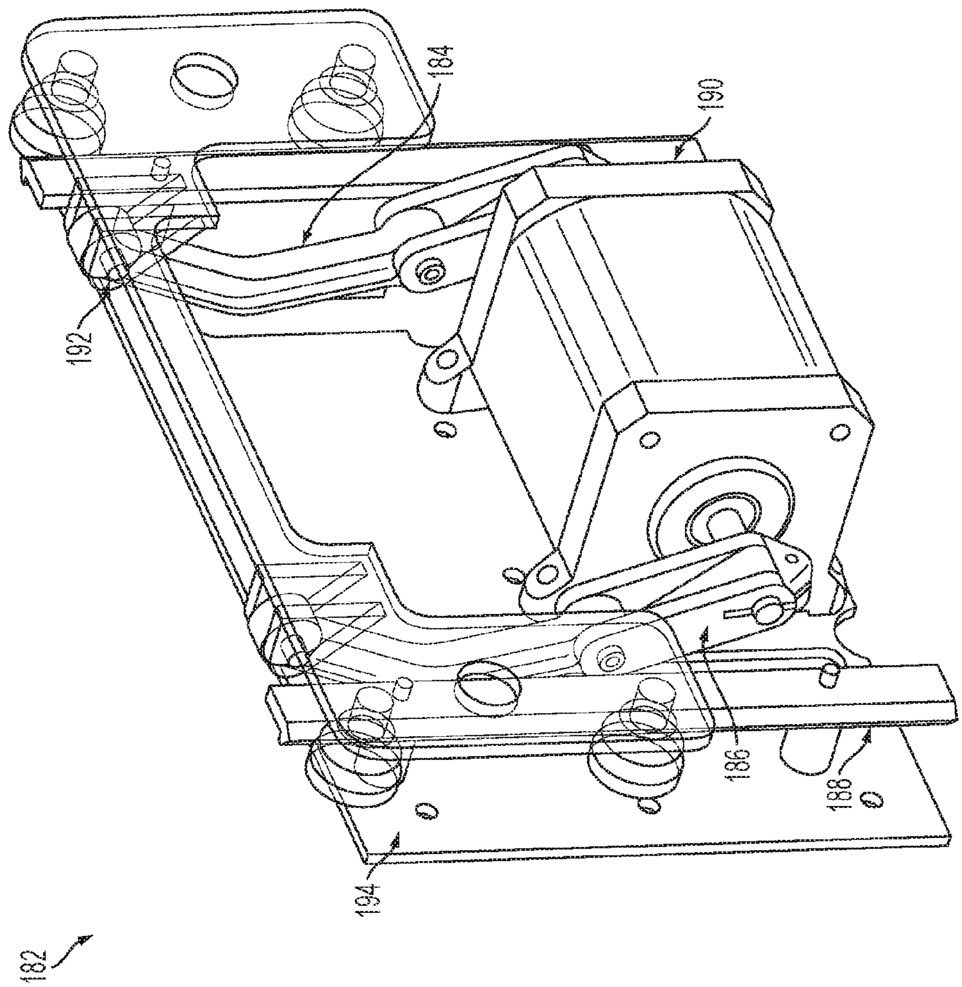

FIG. 27b

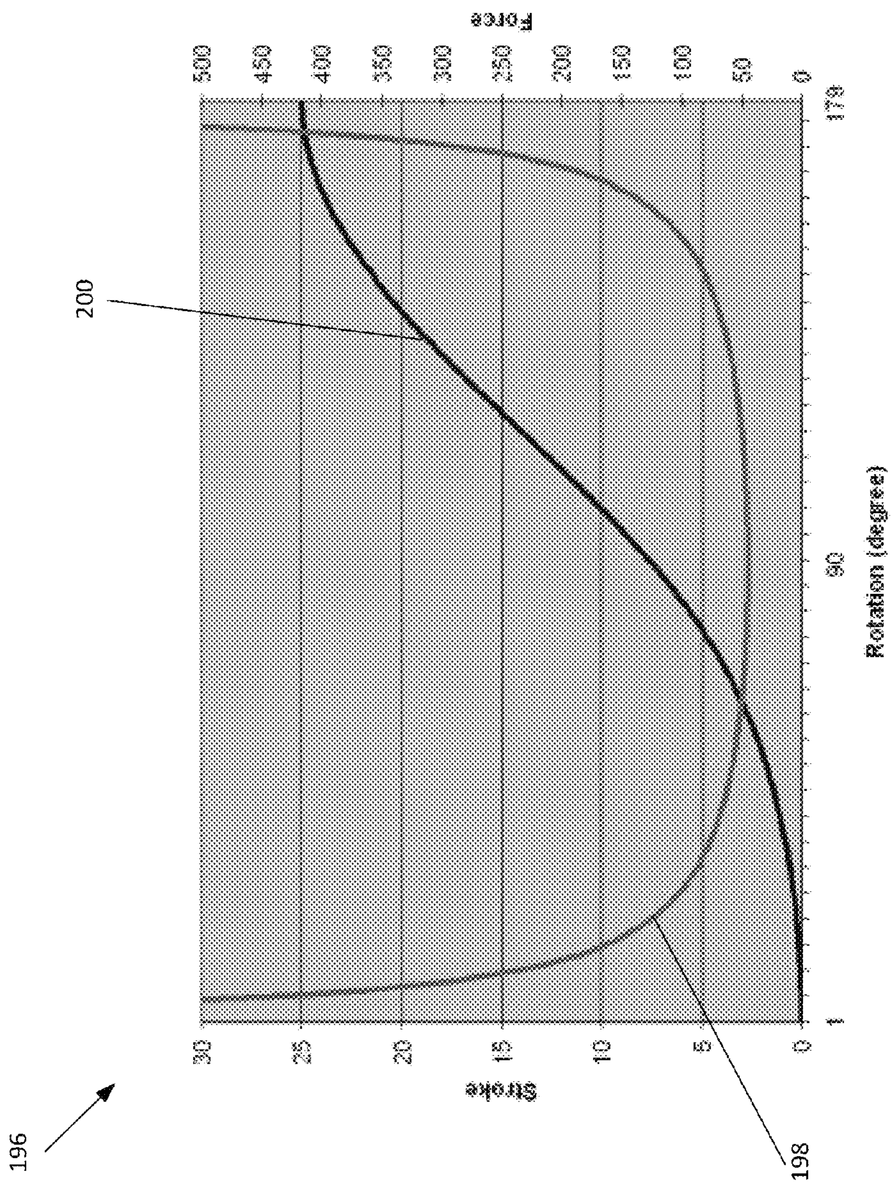
196
198
200
Stroke
Force
Rotation (degree)
0
5
10
15
20
25
30
50
100
150
200
250
300
350
400
450
500
1
90
179

FIG. 28

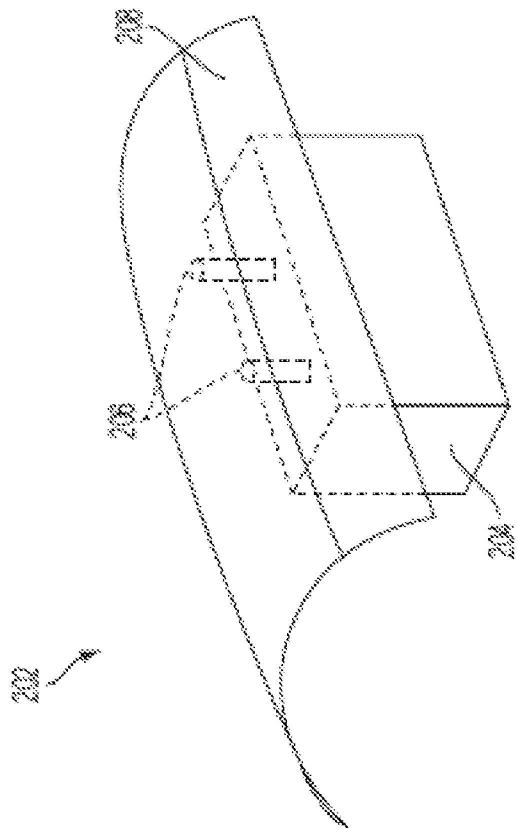

FIG. 29b

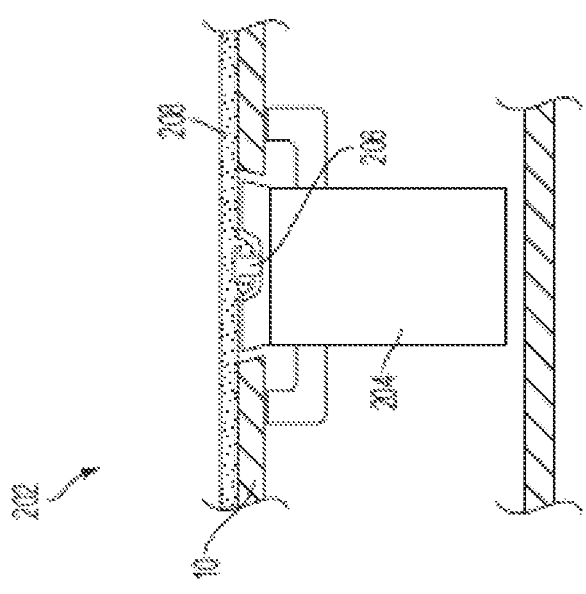

FIG. 29a

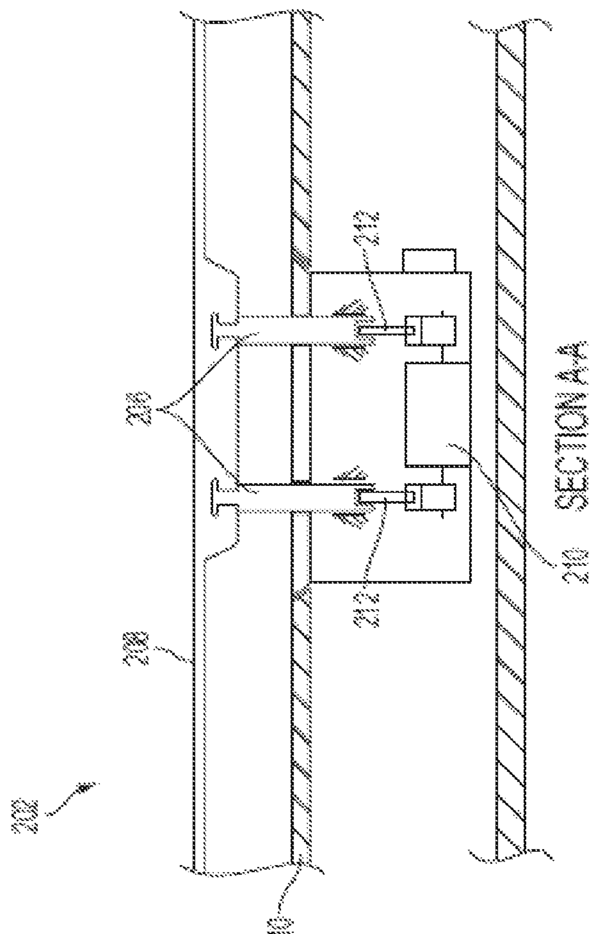

FIG. 29d

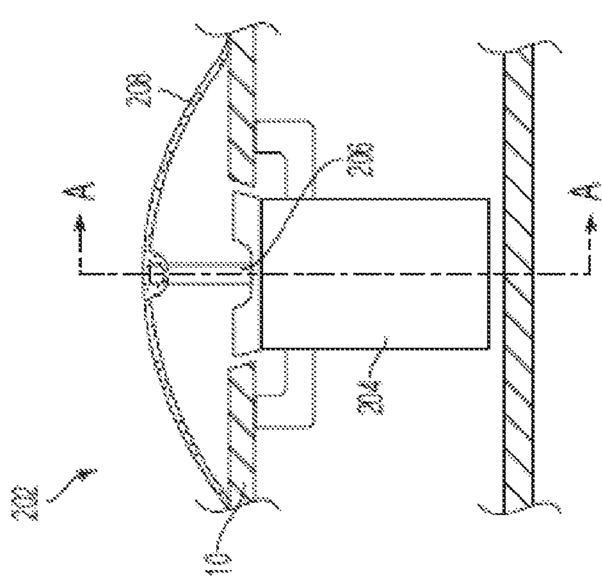

FIG. 29c

ACTUATION MECHANISMS FOR LOAD MANAGEMENT DEVICES ON AERODYNAMIC BLADES

TECHNICAL FIELD

This application relates generally to the design and control of a wind turbine. More particularly, some aspects of the invention relate to modifying the aerodynamics of a wind turbine.

BACKGROUND

With their decreased availability and adverse impact to the environment, fossil fuels and other conventional energy sources are continually declining in popularity while clean, renewable energy source have seen rapid growth. In the coming years, as these fossil fuels continue to become scarce and as knowledge regarding the environmental impact of such energy sources becomes available, the demand for clean, renewable energy will continue to increase. One such source of clean, renewable energy is wind power. For example, kinetic energy from wind may be transmitted into electricity using, e.g., a wind turbine. Accordingly, electricity may be produced without burning any of these costly, environmentally hazardous fossil fuels.

Wind turbines create power proportional to the swept area of their blades. Thus, by increasing the length (e.g., span) of wind turbine blades, more energy may be produced. However, the choice of rotor attributes for a wind turbine, such as its diameter, is a design trade-off between longer blades for more energy production in low winds and shorter blades for load limitation in high winds. A wind turbine having longer blades will increase the swept area, which in turn produces more power. But at high wind speeds, a wind turbine having longer blades places greater demands on the components and creates more situations where the turbine must be shut down to avoid damaging components. Even in situations where the average wind speed is not high enough to cause damage, periodic wind gusts may change both the speed and direction of the wind and apply forces that may be strong enough to damage equipment.

Approaches with varying levels of success have been attempted in achieving higher power, fewer shut downs, and less instances of damage to components. For example, pitch control has been used to vary the pitch of the blade (i.e., the angle of the blade). On a pitch controlled wind turbine, an electronic controller on the turbine checks the power output of the turbine. When the power output exceeds a certain threshold, the blade pitch mechanism turns the rotor blades to reduce the loads on the rotor blades. The blades are later turned back when the wind drops again. However, pitch control can be fairly slow to respond to changes in the wind and is relatively ineffective to loads imparted by sudden wind gusts.

Stall control is another approach that has been used in an attempt to achieve higher power, and to reduce shut downs and damage to components. In passive-type stall controlled wind turbines, the rotor blades are mounted to the hub at a fixed angular orientation. The stall control is achieved passively by the shape of the blade being such that the blade goes into aerodynamic stall (destroying lift) when the wind speed exceeds a certain threshold. Active-type stall controlled wind turbines exist. In such systems, the rotor blades are adjusted in order to create stall along the blade. However, both types of stall control systems can be difficult to optimize and slow to respond, and may suffer from lower predictability of results than desired. These drawbacks are magnified in conditions with erratic winds and wind gusts.

Variable length rotor blade systems have also been used as an attempt to achieve higher power, and experience fewer shut downs and less damage to components. In such systems, the wind turbine rotor blades are telescopic so that their length can be adjusted based on the wind speed. Such provides advantages in that the rotor blades can be extended to provide higher output in low wind conditions and retracted to lower loads in high wind conditions. U.S. Pat. No. 6,902,370, titled "Telescoping Wind Turbine Blade" and which is hereby incorporated by reference in its entirety, discloses a wind turbine system having telescoping wind turbine rotor blades. While variable length rotor blade systems have certain advantages, they may suffer drawbacks in erratic wind conditions or may be too slow to respond when experiencing a wind gust.

More recently, deflectors have been used to control loads on a wind turbine's components. For example, deflectors have been used to disrupt the airflow on a wind turbine blade thus reducing lift and the corresponding load placed on the wind turbine components. For example, U.S. Pat. No. 8,267,654, titled "Wind Turbine with Deployable Air Deflectors" and which is hereby incorporated by reference in its entirety, describes the use of deflectors on a wind turbine blade to control loads. These deflectors are deployed when a sensor or other component senses power production, speed, acceleration, loads, or the like has exceeded a threshold value, and the deflectors are thus deployed to bring the sensed power production, speed, acceleration, loads, etc. back within the threshold. In some instances, multiple deflectors are used on a wind turbine and/or a wind turbine blade to control loads. For example, in some embodiments, multiple deflectors are arranged along the length of a wind turbine blade. Accordingly, one or more of the multiple deflectors may be deployed to control load as discussed above.

However, in order to actuate these one or more air deflectors effectively, actuators must meet certain design characteristics. Because air deflectors may be actuated in response to a sudden change in operating conditions (e.g., a sudden wind gust or the like), actuators may need to be capable of actuating an air deflector quickly (in some embodiments, e.g., 100 ms or less) while delivering an appropriate force to actuate the air deflector (in some embodiments, e.g., 40N). Further, because a mounting space inside a wind turbine blade may be limited, actuators may need to be rather compact. Still further, because over the life of a system an air deflector may be actuated several million, or even hundreds of millions of times, in varying operating conditions, actuators may need to be reliable, resistant to changes in operating conditions, and/or be easily serviceable. Still further, and particularly in applications where multiple air deflectors (and thus actuators) are provided on a single blade, an actuator may need to be rather lightweight in order to, e.g., reduce the centripetal acceleration loading the actuator places the blade.

Thus, there remains a need to provide an actuator for a load management device on a wind turbine (e.g., an air deflector) which exhibits one or more of the above qualities. More particularly, there remains a need to provide an actuator which exhibits appropriate actuation speed/force characteristics, is compact and/or lightweight, and/or is reliable and capable of consistently operating in a variety of operating conditions.

BRIEF SUMMARY

The following presents a simplified summary of the invention in order to provide a basic understanding of some aspects of the invention. This summary is not an extensive overview of the invention. It is not intended to identify key or critical elements of the invention or to delineate the scope of the invention. The following summary merely presents some concepts of the invention in a simplified form as a prelude to the more detailed description provided below.

One or more aspects of the invention provide an actuator for a load management device (e.g., an air deflector) exhibiting one or more of the discussed beneficial characteristics. For example, each actuator may exhibit one or more beneficial qualities for use on, e.g., a wind turbine blade, including appropriate actuation speed/force characteristics, size and/or weight characteristics, and/or increased reliability and consistent operation in a variety of operating conditions.

According to some aspects, a crank slide actuator is provided on a wind turbine blade for actuating one or more load management device. The crank slide actuator may comprise a motor, one or more crank arms coupled to the motor at a first end of the one or more crank arms, and one or more connecting links, wherein a first end of the one or more connecting links is pivotally coupled to a second end of the one or more crank arms, and wherein a second end of the one or more connecting links is pivotally coupled to the load management device, wherein when the motor turns in a first direction the load management device is configured to extend from a blade of a wind turbine, and wherein when the motor turns in a second direction opposite the first direction the load management device is configured to retract into the blade of the wind turbine.

According to other aspects, a wind turbine is provided comprising a hub and a plurality of load management assemblies connected to and arranged about the hub. At least one of the load management assemblies may comprise a crank slide actuator for actuating a load management device on the at least one of the wind turbine blades. In some embodiments, the crank slide actuator may comprise a motor, one or more crank arms coupled to the motor at a first end of the one or more crank arms, and one or more connecting links, wherein a first end of the one or more connecting links is pivotally coupled to a second end of the one or more crank arms, and wherein a second end of the one or more connecting links is pivotally coupled to the load management device, wherein when the motor turns in a first direction the load management device is configured to extend from a blade of a wind turbine, and wherein when the motor turns in a second direction opposite the first direction the load management device is configured to retract into the blade of the wind turbine.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete understanding of the present invention and the advantages thereof may be acquired by referring to the following description in consideration of the accompanying drawings, in which like reference numbers indicate like features, and wherein:

FIG. **1** is a perspective view of a wind turbine according to a first embodiment of the invention;

FIG. **2** is a schematic sectional view of a rotor blade representing airflow under normal wind conditions;

FIG. **3** is a schematic sectional view of the rotor blade of FIG. **2** representing airflow with a load management device in an extended position;

FIG. **4** is cross-section through a rotor blade depicting an air deflector according to one aspect of the invention;

FIG. **5** is an isometric sectional view through the rotor blade depicting the air deflector of FIG. **4** in a retracted position;

FIG. **6** is an isometric sectional view through the rotor blade depicting the air deflector of FIG. **4** in an extended position;

FIG. **7** is a schematic of a rotor blade comprising multiple air deflectors arranged spanwise alone the rotor blade;

FIG. **8** is a schematic of a pneumatic system used to actuate one or more load management devices according to some aspects of the invention;

FIG. **9** is a perspective view of a direct pneumatic actuator configured to actuate one or more load management devices according to some aspects of the invention;

FIG. **10** is a perspective view of a ramp slide pneumatic actuator configured to actuate one or more load management devices according to some aspects of the invention;

FIG. **11** is a perspective view of a scissor actuator configured to actuate one or more load management devices according to some aspects of the invention;

FIG. **12** is a perspective view of a linear induction actuator configured to actuate one or more load management devices according to some aspects of the invention;

FIG. **13** is a perspective view of a belt actuator configured to actuate one or more load management devices according to some aspects of the invention;

FIG. **14** is a perspective view of a closed cam follower actuator configured to actuate one or more load management devices according to some aspects of the invention;

FIG. **15** is a perspective view of a screw drive motor configured to be used in an actuator configured to actuate one or more load management devices according to some aspects of the invention;

FIG. **16** is a front view of a crank configured to be used with the screw drive motor of FIG. **15** in an actuator configured to actuate one or more load management devices;

FIG. **17** is a perspective view of a screw drive actuator configured to actuate one or more load management devices according to some aspects of the invention;

FIG. **18** is a perspective view of a solenoid actuator configured to actuate one or more load management devices according to some aspects of the invention;

FIG. **19** is a perspective view of a rack and pinion actuator configured to actuate one or more load management devices according to some aspects of the invention;

FIG. **20** is a perspective view of a cylindrical cam actuator configured to actuate one or more load management devices according to some aspects of the invention;

FIG. **21** is a perspective view of a Y-belt actuator configured to actuate one or more load management devices according to some aspects of the invention;

FIG. **22** is a perspective view of an offset rotary drive actuator configured to actuate one or more load management devices according to some aspects of the invention;

FIG. **23** is a perspective view of a tape actuator configured to actuate one or more load management devices according to some aspects of the invention;

FIG. **24** is a front view of a rigid tape actuator configured to actuate one or more load management devices according to some aspects of the invention;

FIG. **25** is a front view of a deformable membrane actuator configured to actuate one or more load management devices according to some aspects of the invention;

FIG. **26***a* is a front view of a memory alloy actuator in a retracted state according to some aspects of the invention;

FIG. **26***b* is a front view of the memory alloy actuator depicted FIG. **26***a* in an extended state;

FIG. **26***c* is a front view of the memory alloy actuator depicted in FIGS. **26***a* and **26***b* provided on a wind turbine blade and in an extended state;

FIG. **27***a* is a perspective view of a crank slide actuator configured to actuate one or more load management devices according to some aspects of the invention;

FIG. **27***b* is another perspective view of the crank slide actuator depicted in FIG. **27***a;*

FIG. **28** illustrates a stroke and force plot for the crank slide actuator depicted in FIGS. **27***a* and **27***b* according to some aspects of the invention;

FIG. **29***a* is a side view of a deformable shape actuator configured to actuate one or more load management devices according to some aspects of the invention;

FIG. **29***b* is a perspective view of the deformable shape actuator depicted in FIG. **29***a;*

FIG. **29***c* is a side view of the deformable shape actuator depicted in FIGS. **29***a*-**29***b*; and

FIG. **29***d* is a front view of the deformable shape actuator depicted in FIGS. **29***a*-**29***c* along the line AA depicted in FIG. **29***c*.

DETAILED DESCRIPTION

In the following description of the various embodiments, reference is made to the accompanying drawings, which form a part hereof, and in which is shown by way of illustration various embodiments in which the invention may be practiced. It is to be understood that other embodiments may be utilized and structural and functional modifications may be made without departing from the scope of the present invention.

Aspects of the present invention are directed to actuation mechanisms for one or more load management devices provided on an aerodynamic blade. For example, aspects of the invention are directed to actuators configured to actuate one or more air deflectors disposed on a wind turbine blade.

FIG. **1** shows a wind turbine **2** on a foundation **4** with a tower **6** supporting a nacelle **8**. One or more blades **10** are attached to a hub **12** via a bolt flange **14**. In the depicted embodiment, the wind turbine includes three blades **10**. The hub **12** is connected to a gear box, a generator, and other components within the nacelle **8**. The blades **10** may have a fixed length or may be of the variable length-type, i.e., telescopic, such as shown in FIG. **1**. As shown in FIG. **1**, each variable length blade **10** includes a root or base portion **16** and a tip portion **18**. The tip portion **18** is movable with respect to the root portion **16** so as to controllably increase and decrease the length of the rotor blade **10**, and in turn, respectively increase and decrease the swept area of the rotor blades **10**. Any desirable drive system, such as a screw drive, a piston/cylinder, or a pulley/winch arrangement may be used to move the tip portion **18** with respect to the root portion **16**. Such drive systems are described in U.S. Pat. No. 6,902,370 titled "Telescoping Wind Turbine Blade," which is hereby incorporated by reference in its entirety. The wind turbine **2** further includes a yaw drive and a yaw motor, not shown.

Each rotor blade **10** may include one or more load management devices **28** as schematically depicted in FIG. **3**. The blade **10** depicted in the figures is merely one illustrative cross-sectional design and it is recognized that infinite cross-sectional variations can be used as part of the present invention. The rotor blade **10** may be made of any suitable construction and materials, such as fiberglass and/or carbon fiber. Load management devices **28** located on blade **10** may disrupt the airflow along the rotor blade **10** in order to, e.g., destroy lift at the rotor blade **10** (and thus ultimately reduce rotor speed of the wind turbine **2** and corresponding loads on each of its components). The functionality of load management devices **28** is generally illustrated in FIGS. **2**-**3**. For example, FIG. **2** shows a rotor blade **10** being subjected to airflow under normal wind conditions. Rotor blade **10** has a leading edge **20**, a trailing edge **22**, a high pressure side **24**, and a low pressure side **26**. A chord line c can be defined as a line between the leading edge **20** and trailing edge **22** of the blade **10**. It is recognized that the leading side of the rotor blade **10** corresponds to the leading half of the rotor blade **10** and the trailing side of the rotor blade **10** to the trailing half of the rotor blade **10**.

Without any load management device **28** actuated (as shown in, e.g., FIG. **2**), a lift force created by a difference in pressure between low pressure side **26** and high pressure side **24** will increase as wind speed increases. For example, the more curved surface **26***a* and the opposing less curved surface **24***a* create the dynamics of the low pressure side **26** and the high pressure side **24** due to well-known principles of aerodynamics. This, in combination with the airflow over the rotor blade **10**, creates an effect known as "lift" that assists in the rotation of the rotor. Absent load management devices **28**, in high wind speeds, a wind turbine **2** could experience damaging loads to one or more components. For example, because loads on various components increase as rotor speed of the wind turbine **2** increases, and because the lift created between a difference in pressure on low pressure side **26** and high pressure side **24** will continue to increase with wind speed thus increasing rotor speed of the wind turbine **2**, if wind speeds become too high, wind turbine **2** may experience damaging loads.

Thus, some aspects of the invention utilizes one or more load management devices **28** to disrupt airflow along rotor blade **10** when, e.g., wind speed becomes too high, thus decreasing lift and rotor speed, and reducing the load on wind turbine **2** and its various components. FIG. **3** illustrates rotor blade **10** utilizing load management device **28**. Load management device **28** may be any load management device suitable for disrupting airflow. According to some aspect of the invention, load management device **28** may be, e.g., an air deflector as will be discussed more fully. Load management device **28** is actuated when a sensor determines the rotor blade **10** is exceeding a maximum rated speed of the wind turbine **2** and/or when a sensor senses loads on various components of wind turbine **2** are exceeding threshold values. Load management device **28** induces flow separation along a side of the rotor blade **10** (in the depicted embodiment, along low pressure side **26**). Accordingly, when actuated, load management device **28** may help decrease loads experienced by various components of wind turbine **2** in, e.g., high wind conditions.

FIG. **4** illustrates a cross section of rotor blade **10** employing an air deflector **32** as an example of a load management device **28** according to one or more aspects of the invention. As can be seen in FIG. **4**, rotor blade **10** further includes at least one actuator **30**. Air deflector **32** is movable between an extended position in which the air deflector **32** extends from an exterior surface of the rotor blade **10** and a retracted position in which the air deflector **32** is substantially flush with, recessed from, or otherwise does not materially extend from the exterior surface of the rotor blade **10**. For example, actuator **30** may extend and retract air deflector **32** according to sensed operating conditions when directed by, e.g., a controller (not shown).

FIG. **4** depicts a placement of actuator **30** and air deflector **32** to affect the airflow on the low pressure side **26** of rotor blade **10**. However, in practice, actuator **30** and air deflector **32** may be placed to affect the airflow on the high pressure side **24** of rotor blade **10**. Further, actuator **30** and air deflector **32** may be placed in any position chordwise along rotor blade, such that in some embodiments air deflector **32** will be disposed in the trailing half of rotor blade **10** rather than the leading half as depicted. Further, and as will be discussed more fully, rotor blade **10** may comprise more than one actuator **30** and/or air deflector **32**.

Air deflector **32** may be sized based on the desired wind turbine condition parameter and further in view of the number of load management devices **28** used. Air deflector **32** may be made from any suitable material, such as fiberglass, carbon fiber, stainless steel, plastic, polycarbonate, and/or aluminum, etc. Air deflector **32** may be of any desired width, for example from a few inches to several feet. Additionally, air deflector **32** may extend from the airfoil surface to any desired height, e.g., from less than a percent to a few percent of the chord c, and air deflector **32** may have any suitable thickness based on the material chosen, typically less than one inch.

FIGS. **5-6** are isometric sectional views through the rotor blade **10** depicting the actuator **30** with the air deflector **32** in a retracted position (FIG. **5**) and in an extended position (FIG. **6**). The actuator **30** is suitably mounted by an interface to substantially maintain the surface contour the rotor blade **10**. In another arrangement, the leading face of the actuator **30** may be mounted to the underside of the rotor blade **10**. Suitable fastening arrangements such as hardware and adhesives may be used.

According to some aspects of the invention, multiple load management devices **28** may be provided on a rotor blade **10**. For example, in some embodiments multiple actuators **30** and/or air deflectors **32** may be arranged and spaced spanwise along the length of rotor blade **10**. As illustrated in FIG. **7**, multiple air deflectors **32***a*-**32***i* may be arranged along rotor blade **10**. In FIG. **7**, the remaining components of wind turbine **2** (e.g., other rotor blades **10**, tower **6**, foundation **4**, etc.) have been truncated and/or not depicted for simplicity. However, one skilled in the art given the benefit of this disclosure will appreciate that the two additional rotor blades **10** may comprise multiple air deflectors **32** arranged in a similar fashion as those depicted in FIG. **7**. In such embodiments comprising multiple load management devices **28** (e.g., multiple actuators **30** and/or air deflectors **32**) the number of load management devices **28** actuated (e.g., extended) at any given time may depend on sensed operating conditions of the rotor blade **10** and/or wind turbine **2**. For example, in some instances a sensor (e.g., accelerometer, differential-pressure sensor, speed sensor, power sensor, etc.) may determine that the rotor speed of wind turbine **2** is at or above a maximum rated speed for wind turbine **2**. According, a controller or other suitable device (not shown) may instruct one or more actuators **30** to actuate one or more air deflectors **32** in order to bring the rotor speed and/or loads within an acceptable range.

According to some aspects of the invention, the one or more actuators **30** may be pneumatically operated. In such embodiments, wind turbine **2** may comprise one or more pneumatic systems **33** as depicted in FIG. **8**. Pneumatic system **33** may comprise a compressor unit **36** for, e.g., compressing air to be used in the pneumatic system **33** as is well known in the art. Compressor unit **36** may comprise a compressor, regulator, dryer, and air tank for storing the compressed air. Compressed air from the air tank of compressor unit **36** may be fed to manifold **38**. Manifold **38** may be used to, e.g., direct the compressed air to one or more blades **10** of wind turbine **2**. For example, as depicted in FIG. **8**, in some embodiments manifold **38** may direct compressed air to three blades **10**. The pneumatic system **33** may further comprise one or more actuation devices **40** disposed at one or more blades **10**. For example, in the depicted embodiment, one blade **10** may comprise five actuation devices **40***a*-**40***e*. Each actuation device **40** may comprise, e.g., a pneumatic actuator **41**, a valve **42**, and a load management device **28** (e.g., air deflector **32**, not shown). Each pneumatic actuator **41** may be configured to move between a retract position (e.g., when port "A" in valve **42** connects to pressure port "P" and when port "B" in valve **42** connects to an exhaust port "EB") and an extended position (e.g., when port "A" in valve **42** connects to an exhaust port "EA" and when port "B" in valve **42** connects to a pressure port "P").

For example, in some embodiments, pneumatic actuator **41** may be, e.g., a pneumatic piston. In such embodiments, when valve **42** moves to a retract position (not shown), port "A" connects to pressure port "P" and compressed air is provided to the left side of the pneumatic piston forcing the piston to move from the left to right (e.g., retract). During such movement, because port "B" is connected to exhaust port "EB," any compressed air located on the right side of the pneumatic piston will be exhausted. However, when valve **42** moves to an extend position (as shown in FIG. **8**), port "B" connects to pressure port "P" and compressed air is provided to the right side of the pneumatic piston forcing the piston to move from right to left (e.g., extend). During such movement, because port "A" is connected to exhaust port "EA," any compressed air located on the left side of the pneumatic piston will be exhausted.

According to some aspects of the invention, a load management device **28** (e.g., air deflector **32**) on a wind turbine **2** may be actuated (e.g., extended and retracted) using, e.g., pneumatic system **33**. For example, and as depicted in FIG. **9**, a direct pneumatic actuator **44** (as one example of pneumatic device **40**) may actuate a load management device **28** using pneumatic system **33**. In some embodiments, direct pneumatic actuator **44** may comprise a pneumatic control valve **46**, an electrical connector **48**, a sensing unit **50**, an air line connection **52**, a manifold **54**, an air line **56**, a pneumatic piston **58**, and/or a controller **59**. Further, direct pneumatic actuator **44** may comprise air deflector **32**. For example, pneumatic piston **58** may be coupled to air deflector **32** such that when pneumatic piston **58** moves from, e.g., an extended position to a retracted piston (as discussed), air deflector **32** will be retracted. Similarly, when pneumatic piston **58** moves from, e.g., a retracted position to an extended position, air deflector **32** will be extended.

For example, in some embodiments one or more sensors (including, e.g., sensing unit **50** and/or one or more additional sensing components, not shown) may detect, e.g., one or more aerodynamic loads, etc., acting on a blade **10**. Further, one or more controllers may determine, e.g., that air deflector **32** should be extended in response to the sensed load. Accordingly, controller **59** may instruct pneumatic control valve **46** to move from the "retract" position to the "extend" position. In such embodiments, compressed air may enter direct pneumatic actuator **44** through air line connection **52**, pass through manifold **54** and/or pneumatic control valve **46**, and travel through air line **56** to pneumatic piston **58**, where the pressure of the compressed air moves the pneumatic piston **58** (coupled to air deflector **32**) upward, and thus deploys air deflector **32**. Similarly, if one or more controllers later determine air deflector **32** should be retracted (in response to, e.g., sensed conditions by sensing unit **50**), controller **59** may instruct pneumatic control valve **46** to move from the "extend" position to a "retract position," at which time compressed air will be provided to a top of pneumatic piston **58** and the air previously provided to the bottom of the piston will be exhausted. Accordingly, the pneumatic piston **58** (and thus air deflector **32**) will be retracted.

According to other aspects, a pneumatic actuator **41** may not be directly coupled to the load management device **28** (e.g., air deflector **32**). For example, as depicted in FIG. **10**, ramp slide pneumatic actuator **60** comprises a ramp linkage **66** used to extend and retract air deflector **32**. In order to extend air deflector **32** according to this embodiment, air is provided to pneumatic piston **64** via, e.g., air line **62**, which causes pneumatic piston **64** to move to the left. Because pneumatic piston **64** is coupled to ramp linkage **66**, ramp linkage **66** similarly moves to the left. Further, air deflector **32** may be connected to ramp linkage **66** via a connecting pin **68** disposed in a diagonal slot **67** of ramp linkage **66**. In this embodiment, air deflector **32** is configured to move in an extend/retract direction (e.g., up and down direction) but is not configured to move in a right to left direction. Thus, when ramp linkage **66** moves to the left, connection pin **68** moves up the diagonal slot **67** (e.g., the ramp) and accordingly air deflector **32** is extended. Similarly, when pneumatic piston **64** and ramp linkage **66** move to the right so too does ramp linkage **66**, and the connection pin **68** moves down diagonal slot **67** (e.g., slides down the ramp) and thus air deflector **32** is retracted.

According to other aspects, a pneumatic actuator **41** may be coupled to an air deflector **32** using, e.g., scissor linkage **74** as depicted in FIG. **11**. For example, in some embodiments scissor actuator **70** may comprise, e.g., a pneumatic piston **72**, scissor linkage **74**, one or more pivot pins **75**, air deflector **32** comprising a horizontal slot **73**, and/or connecting pin **71** disposed on the end of one arm of scissor linkage **74** and in horizontal slot **73**. In such embodiments, when pneumatic piston **72** moves to the left, the scissor linkage **74** pivots above pivot pins **75**, and connecting pin **71** slides to the left in horizontal slot **73**. Because (as discussed) air deflector **32** is configured to move up and down but not left to right, when the pneumatic piston **72** moves to the left (causing the arms of scissor linkage **74** to become more vertical) connecting pin **71** moves to the left (in horizontal slot **73**) and up with the end of the arm of scissor linkage **74**, forcing air deflector **32** up (e.g., extending air deflector **32**). Similarly, when pneumatic piston **72** moves to the right (e.g., retracts) the arms of scissor linkage **74** become more horizontal, and connecting pin **71** moves to the right in horizontal slot **73** and down with the end of the arm of scissor linkage **74**, forcing air deflector **32** down (e.g., retracts).

One skilled in the art will appreciate that any of the above pneumatic devices **40** (e.g., direct pneumatic actuator **44**, ramp slide pneumatic actuator **60**, and/or scissor actuator **70**), may be employed using a system other than, e.g., pneumatic system **33**. For example, in some embodiments pneumatic pistons **58**, **64**, and **72** may be replaced by, e.g., a linear induction motor, solenoid, or other electrical motor, etc. (to be more fully discussed) without departing from the scope of this disclosure.

According to some aspects, a load management device **28** (e.g., air deflector **32**) may be actuated using, e.g., linear induction actuator **76** as depicted in FIG. **12**. In some embodiments, linear induction actuator **76** may comprise a translating member **78**, permanent magnets **80**, and electromagnet **82**. Translating member **78** may be, e.g., a component that air deflector **32** is mounted to, or in some embodiments, may be air deflector **32** itself. In the depicted embodiment, permanent magnets **80** are attached to translating member **78**. In operation, when supplied with an electrical current, electromagnet creates a magnetic field which causes translating member **78** (due to permanent magnets **80** attached to translating member **78** and disposed in the created magnetic field) to move in a linear direction (e.g., a direction extending the air deflector **32**). When the electrical current is reversed in electromagnet **82**, a magnetic field created in an opposite direction causes translating member **78** (due to permanent magnets **80** attached to translating member **78** ad disposed in the created magnetic field) to move in an opposite linear direction (e.g., a direction retracting air deflector **32**).

Linear induction actuator **76** may provide one or more of the benefits discussed herein when used on, e.g., a blade **10** of wind turbine **2**. For example, because the components of linear induction actuator **76** may be solid state, linear induction actuator **76** may not comprise, e.g., rotating parts or bearings prone to failure. Further, because drive electronics of linear induction actuator **76** may be isolated from, e.g., a cavity for receiving air deflector **32**, such electronics may be isolated from, e.g., moisture or other contamination. Further, linear induction actuator **76** may be programmed for multiple extension heights and/or motion profiles of air deflector **32** by, e.g., varying the electrical current supplied to electromagnet **82**.

According to some aspects, a belt actuator **84** may be used to actuate one or more load management devices **28** (e.g., air deflector **32**) as depicted in FIG. **13**. In some embodiments, belt actuator **84** may comprise one or more timing belts **88** connected to motor **92** through, e.g., linkage **86**. Although not shown in FIG. **13**, a load management device **28** (e.g., air deflector **32**) may be coupled to timing belts **88** and slidably coupled to linear bearing **94** via, e.g., mounting **93**. In such embodiments, when motor **92** turns the one or more timing belts **88** via linkage **86**, air deflector **32** will move vertically along linear bearing **94** due to air deflector **32** being fixedly coupled to timing belts **88** and slidably coupled to liner bearing **94** via mounting **93**. In some embodiments, belt actuator **84** may comprise one or more position sensors, such as zero position sensor **90**. Such sensors may sense a location of, e.g., air deflector **32** and accordingly provide feedback to motor **92**. For example, in embodiments comprising zero position sensor **90**, when air deflector **32** is being retracted (e.g., when timing belts **88**, fixedly coupled to air deflector **32**, are being turned in a counterclockwise direction when viewed from the right side of belt actuator **84** in FIG. **13**), motor **92** may continue to turn until, e.g., zero position sensor **90** senses that air deflector **32** has been fully retracted. In response, motor **92** may cease turning timing belts **88** (and thus cease retracting air deflector **32**). Other sensors (such as, e.g., halfway position sensors, fully extended position sensors, etc.) may similarly be included in belt actuator **84** (e.g., similar to zero position sensor **90**, an encoder located in motor **92** to sense position, etc.) in order to, e.g., extend or retract an air deflector **32** to any desired position.

Belt actuator **84** may provide one or more of the benefits discussed herein when used on, e.g., a blade **10** of wind turbine **2**. For example, belt actuator **84** may be relatively compact and thus be suitable for mounting within, e.g., a blade **10**. Further, blade actuator **84** may be configured to provide multiple extension heights and/or motion profiles of air deflector **32**.

According to some aspects, a closed cam follower actuator **96** may be used to actuate one or more load management devices **28** (e.g., an air deflector **32**) as depicted in FIG. **14**. In some embodiments, closed cam follower actuator **96** may comprise a cam **98** including slot **99**, air deflector **32**, and a connecting pin **100** attached to air deflector **32** and disposed in slot **99**. A motor (not shown) may rotate cam **98** which, through linkage with connecting pin **100**, extends or retracts air deflector **32** accordingly. For example, air deflector **32** may be configured to move up and down, but may be prevented from moving left or right. Further, and because a counterclockwise-most end of slot **99** is disposed closer radially to a center of cam **98** than a clockwise-most end of slot **99**, when a motor rotates cam **98** counterclockwise, the connecting pin **100** will "follow" slot **99** (e.g., move radially away from a center of cam **98** as thus upwards) and accordingly air deflector **32** will be extended. Further, when a motor rotates cam **98** clockwise, the connecting pin **100** will similarly "follow" slot **99** (e.g., move radially towards a center of cam **98** as thus downwards) and accordingly air deflector **32** will be retracted.

Closed cam follower actuator **96** may provide one or more of the benefits discussed herein when used on, e.g., a blade **10** of wind turbine **2**. For example, in some embodiments a motor center of mass may be disposed close to a skin of blade **10** (e.g., high pressure side **24** or low pressure side **26**). Further, in other embodiments, slot **99** may be configured to provide an optimized force profile according to, e.g., a mounting location of closed cam follower actuator **96** and/or anticipated operating conditions, etc. For example, a smaller slope of slot **99** (e.g., a smaller change in distance from the center of cam **98** to connecting pin **100** per change in position along slot **99**) may lead to a greater force applied to connecting pin **100** (and accordingly, air deflector **32**) than a larger slope of slot **99**. Accordingly, in some embodiments slot **99** may be configured such that a force applied to connecting pin **100**/air deflector **32** is constant along an entire extension and/or retraction stroke of air deflector **32** (e.g., the slope of a slot **99** is constant). In other embodiments, slot **99** may be configured such that a force applied to connecting pin **100**/air deflector **32** is greater during, e.g., a first part of an extension stroke of air deflector **32** (e.g., slot **99** comprises a smaller slope at a first portion of slot **99**). This may be beneficial in order to, e.g., break through a layer of ice or the like which may be covering an opening in blade **10**.

According to some aspects, a screw drive actuator **114** may be used to actuate one or more load management devices **28** (e.g., an air deflector **32**) as depicted in FIG. **17**. In some embodiments, screw drive actuator may comprise, e.g., a screw drive motor **102** as depicted in FIG. **15**. Screw drive motor **102** comprises a motor body **104** and a screw **106**. An interior of motor body **104** may be threaded for receiving screw **106** such that, when operated, motor body **104** rotates screw **106** and linearly translates screw **106** via interior threads. In some embodiments, this screw may be directly coupled to, e.g., air deflector **32** such that the air deflector **32** will move a same linear distance as screw **106**. For example, as depicted in FIG. **17**, screw drive motor **102** may be vertically oriented and coupled to air deflector **32**, such that when screw **106** linearly translates, air deflector **32** extends and/or retracts.

However, in other embodiments, screw drive motor **102** may be connected to air deflector **32** using one or more linkages, such as, e.g., crank **108** as depicted in FIG. **16**. In such embodiments, crank **108** may be configured to pivot about pivot **111**. Further, screw **106** may be coupled to screw connection **110** of crank **108**, and air deflector **32** may be coupled to deflector connection **112** of crank **108**. Thus, when screw drive motor **102** is operated, causing screw **106** to linearly translate, a force applied to crank **108** via screw connection **110** (depicted as "F_{in}" in FIG. **16**) is translated via crank **108** to air deflector **32** at deflector connection **112** (depicted as "F_{out}" in FIG. **16**). In such embodiments, due to a longer length of the arm comprising deflector connection **112** than the arm comprising screw connection **110**, air deflector **32** may move a further distance (e.g., extends or retracts) than screw **106** translates. Accordingly, using crank **108** or the like, in some embodiments screw drive motor **102** may be used even if, e.g., the pitch of the threads on screw **106** is relatively small (e.g., screw **106** moves a relatively small linear distance per each rotation).

According to some aspects of the invention, screw drive motor **102** may be configured to be housed within a load management device **28** such as, e.g., air deflector **32**. For example, screw drive actuator **114** illustrated in FIG. **17** comprises air deflector **32** and screw drive motor **102** housed within air deflector **32**. That is, in at least some vertical positions of air deflector **32** (e.g., fully retracted, less than fully extended, etc.) screw drive motor **102** may be received within an opening provided in air deflector **32**.

Screw drive actuator **114** may provide one or more of the benefits discussed herein when used on, e.g., a blade **10** of wind turbine **2**. For example, in some embodiments screw **106** may be selected according to a force/displacement profile desired for air deflector **32**. That is, in some embodiments, a relatively small pitch of threads may be selected in order to provide a large amount of force applied to air deflector **32**. In other embodiments, a relatively large pitch of threads may be selected in order to provide a relatively large amount of displacement of screw **106** (and according faster actuation speeds) per turn of screw drive motor **102**. Further, for embodiments where screw drive motor **102** is provided within air deflector **32** (as depicted in screw drive actuator **114** in FIG. **17**), such actuators may be relatively compact and thus provide for reduced height requirements at a mounting location of screw drive actuator **114**.

According to some aspects, a solenoid actuator **116** may be used to actuate one or more load management devices **28** (e.g., an air deflector **32**) as depicted in FIG. **18**. In some embodiments, solenoid actuator **116** may comprise solenoid body **118**, electrical leads **119**, and piston **120**. Piston **120** may be configured such that it extends from solenoid body **118** when, e.g., an electrical current is applied to electrical leads **119**. For example, solenoid body **118** may internally comprise a coil of wire (not shown) which creates a magnetic field in the direction of the piston **120** extension when an electric current is applied to the coil accordingly to well-known principles. Accordingly, piston **120**, which may be constructed of a ferrous metal (e.g., steel or iron, etc.) may extend when electrical current is applied to the coil within solenoid body **118**. In such embodiments, piston **120** may be coupled to air deflector **32**, and, when actuated, air deflector **32** may thus extend and/or retract along with the movement of piston **120** relative to solenoid body **118**.

Solenoid actuator **116** may provide one or more of the benefits discussed herein when used on, e.g., a blade **10** of wind turbine **2**. For example, in some embodiments solenoid actuator **116** may provide for very fast actuation times. Further, solenoid actuator containing relatively few moving parts and thus may be reliable and/or robust when incorporated into a wind turbine **2**.

According to some aspects, a rack and pinion actuator **122** may be used to actuate one or more load management devices **28** (e.g., an air deflector **32**) as depicted in FIG. **19**. In some embodiments, rack and pinion actuator **122** may comprise one or more racks **124** coupled to air deflector **32**, and one or more pinions **126** engaged with the one or more racks **124**. In embodiments where rack and pinion actuator **122** comprises more than one rack **124** and correspondingly more than one pinion **126** (such as, e.g., the example depicted in FIG. **19**) each pinion may be linked to one another via linkage **128**. Further, pinion **126** and/or linkage **128** may be coupled to motor **130**. In such embodiments, the engagement of the one or more pinions **126** with the one or more racks **124** causes a movement of air deflector **32** when motor **130** turns. For example, racks **124** and pinions **126** may each comprise gear teeth in mesh engagement with each other. Accordingly, when motor **130** spins in a clockwise direction (when viewed from the left side of the rack and pinion actuator **122** depicted in FIG. **19**), an upward force will be translated from each pinion **126** to each rack **124** causing air deflector **32** to move upward (e.g., extend) by virtue of air deflector's **32** coupling to each rack **124**. Similarly, when motor **130** spins in a counterclockwise direction, a downward force will be translated from each pinion **126** to each rack **124** causing air deflector **32** to move downward (e.g., retract) by virtue of air deflector's **32** coupling to each rack **124**.

Rack and pinion actuator **76** may provide one or more of the benefits discussed herein when used on, e.g., a blade **10** of wind turbine **2**. For example, a radius of pinions **124** may be configured in order to achieve desired speed and/or force requirements. For example, a pinion **124** with a larger radius will cause air deflector **32** to move further for every turn of motor **130** than a pinion **124** with a smaller radius. Thus, an appropriate radius may be selected in order to achieve, e.g., appropriate extension/retraction speeds for air deflector **32**. Further, rack and pinion actuator **122** may be relatively compact and thus may be utilized across a wide variety of mounting locations.

According to some aspects, a cylindrical cam actuator **132** may be used to actuate one or more load management devices **28** (e.g., an air deflector **32**) as depicted in FIG. **20**. In some embodiments, cylindrical cam actuator **132** may comprise cylindrical cam **134** having slot **135**, and connection pin **136** disposed in slot **135** and coupled to, e.g., an air deflector **32** (not shown). Cylindrical cam **134** may be coupled to, e.g., a motor (not shown). As discussed, air deflector **32** may be configured such that it can move up and down, but cannot move left or right. Accordingly, in some embodiments, when cylindrical cam **134** is rotated, connection pin **138** (and accordingly air deflector **32** by of its coupling to connection pin **136**) will "follow" slot **135** up or down. For example, if cylindrical cam **134** is rotated in a clockwise direction (when viewed from the top of cylindrical cam **134** as depicted in FIG. **20**), connection pin **138** will follow slot **135** down causing air deflector to move downwards (e.g., refract). Similarly, if cylindrical cam **134** is rotated in a counterclockwise direction, connection pin **138** will follow slot **135** up causing air deflector to move upwards (e.g., extend).

Cylindrical cam actuator **132** may provide one or more of the benefits discussed herein when used on, e.g., a blade **10** of wind turbine **2**. For example, and as discussed in more detail with respect to closed cam follower actuator **96** depicted in FIG. **14**, slot **135** may be configured in any desirable manner to provide a desired force and/or motion profile along an extension and/or retraction stroke of air deflector **32**.

According to some aspects, a Y-belt actuator **140** may be used to actuate one or more load management devices **28** (e.g., an air deflector **32**) as depicted in FIG. **21**. In some embodiments, Y-belt actuator **140** may comprise single arm **142**, double arm **144**, and Y-connection **146** connecting single arm **142** to double arm **144**. Because Y-connection **146** connects single arm **142** to double arm **144** in the manner shown (e.g., with single arm **142** turned through the space provided on double arm **144**), when a center of Y-belt actuator **140** is rotated (by, e.g., a motor, not shown), single arm **142** may pass between each arm of double arm **144**. Accordingly, in some embodiments a motor may turn a center portion of Y-belt actuator **140** (e.g., the Y-connection **146**) which may rotate nearly 360 degrees (e.g., until Y-connection **146** meets double arm **144**). In some embodiments, one of double arm **144** and single arm **142** may be coupled to, e.g., air deflector **32**. Thus, when a center portion (e.g., Y-connection **146**) of Y-belt actuator **140** is rotated, air deflector **32** may extend and/or retract according to the movement of single arm **142** or double arm **144**.

Y-belt actuator **140** may provide one or more of the benefits discussed herein when used on, e.g., a blade **10** of wind turbine **2**. For example, Y-belt actuator is relatively compact and thus may be utilized in a variety of mounting locations. Further, in some embodiments, Y-belt actuator **140** may provide relatively quick actuation (e.g., extension and/or retraction) speeds. Further, Y-belt actuator may suffer from little or no backlash as is common in other mechanical devices.

According to some aspects, an offset rotary drive actuator **148** may be used to actuate one or more load management devices **28** (e.g., an air deflector **32**) as depicted in FIG. **22**. In some embodiments, offset rotary drive actuator **148** may comprise motor **152**, one or more connecting arms **150** connected to air deflector **32**, pulley **154**, and/or linkage **153**. In some embodiments, pulley **154** may be connected to an output shaft of motor **152** via, e.g., a belt (not shown). Further, each connecting arm **150** may be coupled to pulley **154** via linkage **153**. Accordingly, when motor **152** turns, pulley **154** will also turn due to its connection to motor **152** via, e.g., a belt. Further, when pulley **154** turns, connecting arms **150** may rotate about an axis running through the center of pulley **154** and/or linkage **153** due to connecting arms' **150** connection to pulley **154** and/or linkage **153**. And because connecting arms **150** are coupled to air deflector **32**, when connecting arms **150** rotate about an axis running through the center of pulley **154** and/or linkage **153**, so too does air deflector **32** causing leading edge **155** of air deflector to extend and retract from, e.g., blade **10**. For example, when motor **152** rotates in a clockwise direction (when viewed from the left side of offset rotary drive actuator **148** as depicted in FIG. **22**), pulley **154** will rotate clockwise (via its connection to motor **152**), and accordingly air deflector **32** will rotate clockwise (via its connection to pulley **154** and/or linkage **153** by connecting arms **150**) with the leading edge **155** of air deflector **32** moving upwards (e.g., extending). Similarly, when motor **152** rotates in a counterclockwise direction, pulley **154** will rotate counterclockwise, and accordingly air deflector **32** will rotate counterclockwise with the leading edge **155** of air deflector **32** moving downwards (e.g., retracting).

Offset rotary drive actuator **148** may provide one or more of the benefits discussed herein when used on, e.g., a blade **10** of wind turbine **2**. For example, offset rotary drive actuator **148** may comprise relatively few parts and thus exhibit good reliability and robustness. Further, because air deflector **32** rotates in the manner discussed (rather than, e.g., linearly translating) offset rotary drive actuator **148** may be relatively compact, and thus be suitable for a variety of mounting conditions.

According to some aspects, a tape-style actuator **156** may be used to actuate one or more load management devices **28** (e.g., an air deflector **32**) as depicted in FIG. **22**. In some embodiments, tape-style actuator **156** may comprise cylinder **162** which rotates about axis **158** and comprises notch **160**. Further air deflector **32** may be disposed around a periphery of cylinder **162** with a trailing edge of air deflector **32** abutting notch **160**. In such embodiments, when cylinder **162** rotates counterclockwise (when viewed from the left side of tape-style actuator **156** as depicted in FIG. **23**), notch **160** will engage the trailing edge of air deflector **32**. This engagement will cause air deflector **32** to unwrap from the periphery of cylinder **162** with a leading edge **161** of air deflector **32** rising upward (e.g., extending). Similarly, when cylinder **162** rotates clockwise, air deflector **32** will wrap back around the periphery of cylinder **162** with a leading edge **161** of air deflector **32** moving downward (e.g., retracting).

Rather than wrapping around a periphery of cylinder **162** as depicted in FIG. **23**, in some embodiments air deflector **32** may be, e.g., rigid and coupled to a tape **166** configured to wrap around and unwrap from the periphery of cylinder **162** as depicted in FIG. **24**. In such embodiments, rigid tape actuator **164** may comprise cylinder **162** which rotates about axis **158** and comprises notch **160**, and tape **166** which is coupled to notch **160** at a trailing edge **165** and to a rigid air deflector **32** at a leading edge **167**. Thus, in this embodiment, when cylinder **162** rotates counterclockwise (by, e.g., a motor, not shown) notch **160** engages trailing edge **165** and unwraps tape **166** from the periphery of cylinder **162** with leading edge **167** moving upwards. In such an embodiment, because leading edge **167** is coupled to air deflector **32**, air deflector **32** similarly moves upwards (e.g., extends). When cylinder **162** rotates clockwise, tape **166** wraps around the periphery of cylinder **162** with leading edge **167** moving downwards. And because leading edge **167** is coupled to air deflector **32**, air deflector similarly moves downwards (e.g., retracts).

Tape-style actuator **156** and/or rigid tape actuator **164** may provide one or more of the benefits discussed herein when used on, e.g., a blade **10** of wind turbine **2**. For example, because in some embodiments air deflector **32** will wrap around the periphery of cylinder **162**, a height of tape-style actuator **156** may be compact. Further, tape-style actuator **156** and/or rigid tape actuator **164** may comprise a small number of parts and thus may exhibit desired reliability and robustness characteristics in a variety of operating conditions.

According to some aspects, a deformable membrane actuator **168** may be used to actuate one or more load management devices **28** as depicted in FIG. **25**. In some embodiments, deformable membrane actuator **168** may comprise a cylinder **173** comprising a cam **172** and a deformable membrane **170** which, in combination, comprise a load management device **28**. For example, cylinder **173** may be configured to rotate about axis **174** when, e.g., engaged with a motor (not shown). When a portion of cylinder **173** not comprising cam **172** abuts deformable membrane **170**, deformable membrane **170** may be in a first, unreformed state. In such a state, deformable membrane **170** may, e.g., seamlessly form a part of high pressure side **24** or low pressure side **26** of blade **10**. However, as cylinder **173** rotates about axis **174** and cam **172** comes into contact with deformable membrane **170**, deformable membrane may deform to accommodate cam **172**. In such a second, deformed state (as depicted in FIG. **25**), the combination of cam **172** and deformable membrane **170** extends beyond a surface of blade **10** to form load management device **28**. Deformable membrane **170** may be made of any suitable material to form a semi-rigid surface capable of deforming when in contact with, e.g., cam **172**, and in some embodiments may be, e.g., a stainless steel sheet.

Deformable membrane actuator **168** may provide one or more of the benefits discussed herein when used on, e.g., a blade **10** of wind turbine **2**. For example, deformable membrane actuator **168** may be relatively light and compact. Further, because deformable membrane actuator **168** does not comprise an opening along a surface of blade **10** in order to, e.g., deploy air deflector **32** or the like, deformable membrane actuator may be resistant to, e.g., moisture and other contamination and thus exhibit desired characteristics of reliability and robustness. Still further, embodiments employing deformable membrane actuator **168** may comprise a smooth surface along, e.g., high pressure side **24** and/or low pressure side **26** of blade **10**, with no parts of the actuator (beyond, e.g., an outer surface of deformable membrane **170**) exposed outside of the blade **10**.

According to some aspects, a memory alloy actuator **176** may be used to actuate one or more load management devices **28** as depicted in FIGS. **26***a*-**26***c*. In some embodiments, memory alloy actuator **176** may comprise a memory alloy deflector **178** and one or more Peltier chips **180**. Memory alloy deflector **178** may be made of a memory alloy which may be configured to move between one or more states when heated and/or cooled. For example, FIG. **26***a* illustrates memory alloy deflector **178** in a first state and FIG. **26***b* illustrates memory alloy deflector **178** in a second state. In some embodiments, memory alloy deflector **178** may be configured to move to the first state when, e.g., sufficiently cooled, and may be configured to move to the second state when, e.g., sufficiently heated. In other embodiments, memory alloy deflector **178** may be configured to move to the first state when, e.g., sufficiently heated, and may be configured to move to the second state when, e.g., sufficiently cooled. Memory alloy actuator **176** may further comprise one or more Peltier chips **180** which may be configured to, e.g., heat and/or cool memory alloy deflector **178** when an electric current is applied to Peltier chip **180**. Accordingly, in some embodiments, an electric current may be applied to the one or more Peltier chips **180** in order to, e.g., sufficiently heat or cool the surrounding memory allow deflector **178**. In such embodiments, the memory alloy deflector **178**, when sufficiently heated or cooled, will move to either the first (e.g., retracted) or second (e.g., extended) state. Thus, as illustrated in FIG. **26***c*, when memory alloy actuator **176** is attached to a blade **10**, memory alloy actuator **176** may act as a load management device **28**. For example, when in a first state (as depicted in, e.g., FIG. **26***a*) memory alloy actuator **176** may lay relatively flat along a top surface of blade **10** and thus not affect, e.g., airflow and/or lift along the blade **10**. However, when in a second state (as depicted in, e.g., FIGS. **26***b* and **26***c*) memory alloy actuator **176** may extend from blade **10** and sufficiently disrupt lift along blade **10** (and thus reduce load).

Memory alloy actuator **176** may provide one or more of the benefits discussed herein when used on, e.g., a blade **10** of wind turbine **2**. For example, memory alloy actuator may comprise relatively few parts, and thus may exhibit desired reliability and robustness characteristics. Further, memory alloy actuator **176** may be relatively compact and lightweight, and thus may be installed in a number of mounting locations and may have minimal impact on, e.g., centripetal loading of blade **10**, etc.

According to some aspects, a crank slide actuator **182** may be used to actuate one or more load management devices **28** (e.g., an air deflector **32**) as depicted in FIGS. **27***a*-**27***b*. In some embodiments, crank slide actuator **182** may comprise a motor **190** coupled to one or more crank arms **186**, which may be pivotally coupled to one or more connecting links **184**. The one or more connecting links **184** may also be pivotally coupled to air deflector **32** by joint pins **192** at an opposite ends of connecting links **184** than are pivotally coupled to crank arms **186**. Air deflector **32** may further be slidably connected to one or more tracks **188**. In some embodiments, crank slide actuator **182** may be mounted to, e.g., a frame of blade **10** or other housing by mounting plate **194**.

FIG. **27***a* illustrates a right-front perspective view of crank slide actuator **182** and air deflector **32** in a retracted state. In such an embodiment, the one or more crank arms **184** may be generally vertical with a majority of each disposed below a shaft of motor **190**. Further, the one or more connecting links **184** may be angled such that, in the retracted state (FIG. **27***a*) a bottom end of each connecting link **184** is pivotally connected to a bottom end of a crank arm **184**, a top end of each connecting link **184** is pivotally connected to air deflector **32** via joint pins **192**, and a center portion of each connecting link **184** angles around a portion where a shaft of motor **190** is coupled to the corresponding crank arm **186**. In such a state, a portion of each connecting link **184** (e.g., approximately half of each connecting link **184**) is disposed below a shaft of motor **190** and is abutted to a crank arm **186**. FIG. **27***b* illustrates a left-rear perspective view of crank slide actuator **182** in an extended state. In such a state, the one or more crank arms **184** may be generally vertical, however now a majority of each is disposed above the shaft of motor **190**. Further, in this state, a majority of each connecting link **184** is disposed above each of the crank arms **186** and no longer abuts each of the crank arms **186**. In operation, when motor **190** turns, the one or more crank arms **186** and one or more connecting links **184** will move from the first (retracted) position to the second (extended) position and thus extend air deflector **32**, or move from the second (extended) position to the first (retracted) position and thus retract air deflector **32**.

For example, when the motor **190** turns clockwise (when viewed from the right side of crank slide actuator **182** as depicted in FIG. **27***a*) from the retracted position as depicted in FIG. **27***a*, crank arm **186** will correspondingly rotate, thus lifting connecting link **184** via each crank arm's **186** pivot connection to connecting link **184**. Air deflector **32** (via its connection with the one or more connecting links **184**) will thus lift (extend) accordingly by slidably translating along track **188**. Similarly, from the extended position depicted in FIG. **27***b*, when the motor **190** turns counterclockwise (when viewed from the left side of crank slide actuator **182** as depicted in FIG. **27***b*) the crank arms **186** will correspondingly rotate counterclockwise, thus lowering (retracting) connecting links **184** and thus air deflector **32** along tracks **188**. Because air deflector **32** may be slidably connected to one or more tracks **188** and pivotally connected to connecting links **184** via joint pins **192**, when moved from the retracted to the extended state or from the extended to the retracted state, air deflector **32** linearly translates between the retracted and extended positions. In some embodiments, motor **190** may turn, e.g., approximately 180 degrees between the first state and the second state.

Crank slide actuator **182** may provide one or more of the benefits discussed herein when used on, e.g., a blade **10** of wind turbine **2**. For example, crank slide actuator **182** may be relatively compact and thus be suitable for a variety of mounting locations. Further, crank slide actuator may provide relatively high extension and/or retraction speeds and thus suitably extend or retract, e.g., air deflector **32** from a blade **10** in a desired time (in some embodiments, e.g., 100 ms or less). Further, because each of crank arms **186** and connecting links **184** are generally vertical in a retracted position and in an extended position, crank slide actuator **182** may exhibit a natural "locked" condition when in each position, thus providing ample support to keep the air deflector **32**, e.g., either locked in a retracted position or in an extended position.

Still further, crank slide actuator **182** may provide a desirable force profile along the stroke of air deflector **32** for extending and/or retracting air deflector **32**. This may be more readily understood with reference to FIG. **28**. FIG. **28** illustrates a stroke and force plot **196** according to some embodiments of crank slide actuator **182**. For example, force curve **198** depicts a force exerted on air deflector **32** as a function of rotation angle of the motor **190**/crank arms **186**, and stroke plot **200** depicts displacement of air deflector **32** as a function of rotation angle of the motor **190**/crank arms **186**. As seen, the change in stroke (e.g., displacement) of air deflector **32** is less per degree of rotation near 0 degrees of rotation (corresponding to a retracted position) and 180 degrees of rotation (corresponding to an extended position) than, e.g., near 90 degrees of rotation. Further, the force acting on air deflector **32** is greatest near 0 degrees of rotation and 180 degrees of rotation. Thus, according to some embodiments, of crank slide actuator **182** may provide a greater force to air deflector **32** at the beginning (e.g., retraction position) and end (e.g., extended position) of the air deflector's **32** stroke, and may cause more displacement of air deflector **32** per degree of motor **190** rotation in the middle of air deflector's **32** stroke. Such a force profile may be beneficial in order to, e.g., break ice covering an opening of air deflector **32**, etc.

According to some aspects, a deformable shape actuator **202** may be used to actuate one or more load management devices **28** as depicted in FIGS. **29***a*-**29***d*. In some embodiments, deformable shape actuator **202** may comprise an actuator body **204**, a deformable deflector **208**, and connecting links **206** coupling actuator body **204** to deformable deflector **208**. Actuator body **204** may further comprise, e.g., one or more of the actuators or components of one more actuators described herein. For example, in some embodiments actuator body **204** may comprise, e.g., one or more crank arms **212** connected to a motor **210** similar to the one or more crank arms **186** connected to motor **190** as discussed in connection with respect to FIGS. **27***a*-**27***b*. In such embodiments, actuator body **204** may function similar to crank slide actuator **182** as discussed, however, connecting links **206** may be coupled to deformable deflector **208** (rather than pivotally coupled to air deflector **32** in the manner discussed with respect to crank slide actuator **182**).

In operation, actuator body **204** may be configured to move between a first (e.g., retracted) state as depicted in FIG. **29***a*, and a second (e.g., extended) state as depicted in FIGS. **29***b*, **29***c*, and **29***d*. Deformable deflector **208** may seamlessly form a portion of the surface of blade **10** (e.g., high pressure side **24** or low pressure side **26**) such that in each state there are no exposed openings in blade **10**. For example, and as depicted in FIG. **29***a*, when actuator body **204** (and accordingly deformable deflector **208**) is in the first (e.g., retracted) state, deformable deflector **208** may not obstruct air flow along blade **10** (e.g., may not affect lift). However, and as depicted in FIGS. **29***b*, **29***c*, and **29***d*, when actuator body **204** moves to a second (e.g., extended) state, connecting links **206** may extend causing deformable deflector **208** to deform (and thus extend) with the edges thereof, e.g., sealed or otherwise affixed to blade **10**. Accordingly, in this second (e.g., extended) state, deformable deflector **208** may obstruct air flow along blade **10** (e.g., destroy lift) without providing an exposed opening or the like in blade **10**. Deformable deflector **208** may be made of any suitable material configured to move (e.g., deform) between the first state and the second state, and in some embodiments may be, e.g., a stainless steel sheet or the like.

As discussed, in some embodiments actuator body **204** may comprise one or more components similar to those provided in, e.g., crank slide actuator **182**. This may be more fully appreciated with reference to FIGS. **29***c* and **29***d*. FIG. **29***c* illustrates a side view of deformable shape actuator **202** according to some aspects. FIG. **29***d* illustrates a front view of deformable shape actuator **202** along line AA as depicted in FIG. **29***c*. As illustrated, actuator body **204** may comprise motor **210** and one or more crank arms **212** pivotally coupled to the one or more connecting links **206**. In this regard, actuator body **204** may comprise components similar to crank slide actuator **182** discussed in connection with FIGS. **27***a* and **27***b*. Accordingly, motor **210**, crank arms **212**, and connecting links **206** may operate in a similar manner as motor **190**, crank arms **186**, and connecting links **184**, respectively. Thus, in operation, deformable shape actuator **202** may actuate (e.g., extend and retract) deformable deflector **208** in a similar manner to that of crank slide actuator **182** actuating (e.g., extending and retracting) air deflector **32** as discussed. It will be appreciated by one skilled in the art, given the benefit of this disclosure, that in other embodiments actuator body **204** may comprise components from, e.g., any of the other actuators discussed herein without departing from the scope of this disclosure.

Deformable shape actuator **202** may provide one or more of the benefits discussed herein when used on, e.g., a blade **10** of wind turbine **2**. For example, and as illustrated in FIG. **29***b*, an actuator body **204** of deformable shape actuator **202** may be relatively compact and/or lightweight. That is, actuator body **204** may comprise a smaller width and/or length dimension than deformable deflector **208** and thus be suitable for mounting in a variety of mounting locations. Further, deformable deflector **208** may be relatively lightweight providing for fast actuation times. And because deformable deflector **208** may conform to blade **10** in an airtight or nearly airtight manner, deformable shape actuator **202** may comprise relatively few parts (e.g., a seal around an opening for a load management device **28** or the like is not needed) and may be less vulnerable to, e.g., moisture or other contamination.

Although not described in detail with respect to any of the discussed embodiments, any of the actuation mechanisms described herein may be configured to actuate a load management device **28** to variable heights. For example, with respect to pneumatic systems, multiple pneumatic pistons of varying lengths may be incorporated into each of the described actuators. Accordingly, an appropriately sized pneumatic piston may be actuated depending on a desired extension height of the load management device **28**. In other embodiments, where an electrical motor is utilized, a stepper motor or other motor may be utilized and programmed to, e.g., stop at variable heights, etc.

Further, one or more of the above actuators may be combined on a single wind turbine **2** and/or wind turbine blade **10** without departing from the scope of the invention. For example, and returning to FIG. **7**, a wind turbine **2** and/or wind turbine blade **10** comprising multiple air deflectors **32** (e.g., air deflectors **32***a*-**32***i*) may employ one of the discussed actuators to actuate one or more inboard air deflectors **32** (e.g., air deflectors **32** disposed near root **35**) while employing a different one of the discussed actuators to actuate one of more outboard air deflectors **32** (e.g., air deflectors **32** disposed near tip **37**). Accordingly, an appropriate actuator may be chosen according to, e.g., space constraints, required force/speed, etc., for a particular spanwise location of a corresponding air deflector **32**.

In some embodiments, a shape of load management device **28** and/or air deflector **32** used in any actuator may vary from those depicted without departing from the scope of the disclosure. For example, in some embodiments a leading edge (e.g., extended edge) of a load management device **28** or air deflector **32** used in any of the above actuators may be e.g., rounded, angled, etc., without departing from the scope of this disclosure. In other embodiments, a deformable shape deflector (such as, e.g., deformable deflector **208** depicted in FIGS. **29***a*-**29***d*) may be replace any of the load management devices **28** and/or air deflectors **32** depicted with respect to the discussed actuators. Any other desired shape and/or configuration of load management device **28** and/or air deflector **32** may be provided to any of the discussed actuators without departing from the scope of this disclosure.

The methods and features recited herein may further be implemented through any number of computer readable media that are able to store computer readable instructions. Examples of computer readable mediums that may be used include RAM, ROM, EEPROM, flash memory, or other memory technology, CD-ROM, DVD or other optical disk storage, magnetic cassettes, magnetic tape, magnetic storage and the like.

While illustrative systems and methods as described herein embodying various aspects of the present invention are shown, it will be understood by those skilled in the art that the invention is not limited to these embodiments. Modifications may be made by those skilled in the art, particularly in light of the foregoing teachings. For example, each of the elements of the aforementioned embodiments may be utilized alone or in combination or subcombination with elements of the other embodiments. It will also be appreciated and understood that modifications may be made without departing from the true spirit and scope of the present invention. The description is thus to be regarded as illustrative instead of restrictive on the present invention.

We claim:

1. An actuator for actuating a load management device on a blade of a wind turbine comprising:

a motor;

one or more crank arms coupled to the motor at a first end of the one or more crank arms; and

one or more connecting links, wherein a first end of the one or more connecting links is pivotally coupled to a second end of the one or more crank arms, and wherein a second end of the one or more connecting links is pivotally coupled to the load management device,

wherein when the motor turns in a first direction the load management device is configured to extend from a blade of a wind turbine, and wherein when the motor turns in a second direction opposite the first direction the load management device is configured to retract into the blade of the wind turbine,

wherein the motor is configured to turn from a first position to a second position, wherein the first position corresponds to a retracted position of the load management device, and wherein the second position corresponds to an extended position of the load management device, and

wherein the one or more crank arms extend lengthwise in a direction parallel to a surface of the load management device when the motor is in the first position and when the motor is in the second position.

2. The actuator of claim **1** further comprising one or more tracks extending in a direction in which the load management device is configured to extend and retract, wherein the load management device is slidably coupled to the one or more tracks.

3. The actuator of claim **1**, wherein when the motor turns from the first position to the second position, a shaft of the motor rotates 180 degrees.

4. The actuator of claim **1**, wherein when the motor is in the first position a majority of the one or more crank arms is disposed below a shaft of the motor.

5. The actuator of claim **1**, wherein when the motor is in the second position a majority of the one or more crank arms is disposed above a shaft of the motor.

6. The actuator of claim **1**, wherein the one or more connecting links comprises an angled portion having a vertex, and wherein when the motor is in the first position, the vertex abuts a location of the of the one or more crank arms where the first end of the one or more crank arms is coupled to the motor.

7. The actuator of claim **1**, wherein a force transferred from the motor to the load management device when the motor moves to the second position is greater when the motor begins in the first position than when the motor halfway between the first position and the second position.

8. The actuator of claim **1**, wherein a force transferred from the motor to the load management device when the motor moves to the first position is greater when the motor begins in the second position than when the motor begins halfway between the second position and the first position.

9. The actuator of claim **1**, wherein the one or more connecting links extend lengthwise in a direction parallel to a surface of the load management device when the motor is in the first position and when the motor is in the second position.

10. The actuator of claim **1**, wherein the load management device is positioned on a mid-chord location of the blade.

11. A wind turbine comprising:

a hub; and

a plurality of wind turbine blades connected to and arranged about the hub, wherein at least one wind turbine blade of the plurality of wind turbine blades comprises an actuator for actuating an air deflector on the at least one wind turbine blade, wherein the actuator comprises:

a motor;

one or more crank arms coupled to the motor at a first end of the one or more crank arms; and

one or more connecting links, wherein a first end of the one or more connecting links is pivotally coupled to a second end of the one or more crank arms, and wherein a second end of the one or more connecting links is pivotally coupled to the air deflector,

wherein when the motor turns in a first direction the air deflector is configured to extend from the at least one wind turbine blade, and wherein when the motor turns in a second direction opposite the first direction the air deflector is configured to retract into the at least one wind turbine blade,

wherein the motor is configured to turn from a first position to a second position, wherein the first position corresponds to a retracted position of the air deflector, and wherein the second position corresponds to an extended position of the air deflector, and

wherein the one or more crank arms extend lengthwise in a direction parallel a surface of the air deflector when the motor is in the first position and when the motor is in the second position.

12. The wind turbine of claim **11**, wherein the actuator further comprises one or more tracks extending in a direction in which the air deflector is configured to extend and retract, wherein the air deflector is slidably coupled to the one or more tracks.

13. The wind turbine of claim **11**, wherein when the motor turns from the first position to the second position, a shaft of the motor rotates 180 degrees.

14. The wind turbine of claim **11**, wherein when the motor is in the first position a majority of the one or more crank arms is disposed below a shaft of the motor.

15. The wind turbine of claim **11**, wherein when the motor is in the second position a majority of the one or more crank arms is disposed above a shaft of the motor.

16. The wind turbine of claim **11**, wherein the one or more connecting links comprises an angled portion having a vertex, and wherein when the motor is in the first position, the vertex abuts a location of the one or more crank arms where the first end of the one or more crank arms is coupled to the motor.

17. The wind turbine of claim **11**, wherein a force transferred from the motor to the air deflector when the motor moves to the second position is greater when the motor begins in the first position than when the motor begins halfway between the first position and the second position.

18. The wind turbine of claim **11**, wherein a force transferred from the motor to the air deflector when the motor moves to the first position is greater when the motor begins in the second position than when the motor begins halfway between the second position and the first position.

19. The wind turbine of claim **11**, wherein the one or more connecting links extend lengthwise in a direction parallel to a surface of the air deflector when the motor is in the first position and when the motor is in the second position.

20. The wind turbine of claim **11**, wherein the air deflector is positioned on a mid-chord location of the at least one wind turbine blade.

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